Intelligent Egress

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Declaration

I declare that this thesis has been composed solely by myself, with the support of Dr Stephen Welch, and that it has not been submitted, either in whole or in part, in any previous application for a degree. Except where otherwise acknowledged, the work presented is entirely my own.

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Abstract

Intelligent egress proposes a novel approach to enhancing the safety of evacuations from fire emergencies by means of way-finding systems that exploit real time information gathered from building sensor data. In standard approaches to fire evacuations in the built environment, occupants are rarely provided with any information that could aid egress path selection. It is well known that occupants unfamiliar with a building will often re-trace their original route of ingress, or simply follow others. These factors can lead to inefficiencies that can violate design assumptions on egress route utilisation, resulting in a greater possibility of increased evacuation time and unnecessary queuing, creating a higher risk of occupants being exposed to hazardous conditions.

This project has demonstrated the potential benefit of installing an intelligent egress system, across a range of building complexities, by use of simulated evacuations. BRE has developed the Monte-Carlo risk assessment tool, CRISP, which has been used throughout the project. A novel dynamic route planning system has been developed to utilise live sensor data from these CRISP simulations to produce effective evacuation plans in real time. The sensor data is constantly reviewed, with the selected paths being altered where appropriate. By directing occupants along safer paths it was possible to reduce overall exposure to danger with steered and un-steered evacuations being compared, using fractional equivalent dose (FED) as the means of discrimination. To represent the high probability that occupants will not always follow instructions during a real life event, a variety of obedience levels were also considered.

Results indicated that the more complex the building layout and the more available egress routes the greater the potential benefits of increased system sophistication. The importance of the dynamic aspect of the system, updating route instructions according to the evolving environment has been demonstrated for all but the most benign fire events. Tests with instruction obedience of 50% have also been shown to result in lower FED levels than for un-steered evacuations. The benefits of modifying the system to the particulars of a building layout, by implementing specifically designed heuristics is also discussed. The potential benefits of a sensor driven dynamic route planning system have been conclusively demonstrated, which should encourage further investigation.

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Nomenclature

Dynamic Route Planning System (DRPS) – Focal point of intelligent egress system. Utilises sensor and past movement data to produce evacuation plans.

Static Occupant Steering – Steering occupants only after the first detection of a hazard and not thereafter reviewing sensor data or updating path instructions.

Dynamic Occupant Steering – Constantly reviewing sensor data and updating path instructions where necessary.

Egress Solution – A set of paths, from detected location, to a place of safety, with one for each occupant.

Global Safest Solution (GSS) – Egress solution with the lowest determined overall exposure to danger summed across all occupants.

System Execution – Run of entire system: Reading and interpreting sensor data and the generation and selection of egress solutions.

Universal Fastest Path Set (UFP) – The shortest safest, or equal safest, path from each occupied location to a place of safety.

Multiple Solution Run (MSR) – A system execution where multiple solutions are generated and evaluated to determine the (GSS)

Single Solution Execution (SSE) – System execution where only the GSS is considered.

1 Introduction

Presented in this thesis, is a system that aims to improve evacuation efficiency by proposing a novel method for exploiting live information derived from building sensor data. This system will be referred to as "Intelligent Egress". Traditional approaches to evacuation result in occupants receiving little or no direction in how to proceed during an event requiring egress, over and above the standard green emergency exit signs. Familiarity with this type of sign can result in occupants becoming desensitised and re-tracing their original route of ingress, or simply following others, leading to violation of assumptions regarding escape route utilisation made on building design.

Modern buildings are often equipped with sensors of various types that can be used for smoke detection and occupant comfort. These can potentially be exploited for use in emergency scenarios by both evacuees and emergency services. The idea of intelligent egress is to use this sensor data to generate evacuation plans in real time. These plans would be based on a higher level of knowledge than any plans designed during design or construction of the building and therefore increasing the likelihood of successful egress for all occupants.

Before any building owner is going to consider installing a conceivably expensive intelligent egress system, it is necessary to make available a thorough and robust demonstration of the possible advantages of implementing such a system. An obvious first step is to use simulated evacuations to represent a real fire event requiring egress and use these as a foundation for further exploration. The use of computational models has several advantages over live evacuation trials. For instance, the costs associated with arranging a full scale evacuation, when a building of sufficient size is required to provide a complex enough environment to allow proper demonstration of an intelligent egress system, are likely to be prohibitively high. Moreover, the main advantage of live tests, which would be to provide more realistic human behaviour than can be recreated by simulations, is negated by the fact that occupants will almost always be aware that the evacuation is a trial, and may not act as they would in a real emergency. The level of flexibility provided by egress models is also much greater, as it is possible to test a large range of building layouts, fire types and population distributions.

In addition to this it should be noted that computational models have been used extensively throughout the field of fire safety engineering. Such techniques have been applied to investigations to determine the cause of a fire, performance of critical fire safety measures in place (such as detectors and sprinklers), risk assessment, etc. [1].

Motivation for this thesis is easily explained. Despite an overall decreasing trend in recent decades, fatalities caused by fire emergencies in the built environment remains an unacceptably frequent event. When fatalities due to fire occur in large, more complex buildings the cause is often down to occupants not receiving relevant information of a high enough quality [2].

Emergency response can also potentially benefit from intelligent egress, as increased information derived from live data could aid in better decisions being made. An obvious real life example where emergency response entered a highly dangerous environment is the World Trade Centre collapse on September 11^{th} 2001[3].

As such, using the egress model, CRISP [4], developed at BRE, to represent real fire emergencies in the built environment, this project will aim to demonstrate the potential benefits of an intelligent egress system. A novel dynamic route planning system (DRPS) has been developed which utilises simulated sensor data regarding occupant location, hazard location and severity and the on/off state of detectors, in order to generate "safe" evacuations plans, in real time. Occupants within the simulated environment are then steered along the evacuation routes generated by the DRPS. Various methods of steering are employed, presenting a range of possible levels of system sophistication. Variations in sophistication include but aren't limited to how often the route instructions would be revised considering the possibility of evolving hazard conditions and the range of possible paths considered for each occupant.

The idea of using accumulated occupant movement data to improve the precision of predictions of future egress flow patterns is also investigated. Details of all aspects of the proposed system are presented in chapter 2. To determine whether or not the impact of the system is positive, DRPS steered simulations and un-steered simulations, with the same initial conditions, are compared. The measure of evacuation success or safety is the sum of the CRISP computed fractional equivalent dose (FED) value for all occupants. Throughout the project, the complexity of the scenario in which the DRPS is demonstrated and tested, evolves from a simple single floor building to more complex multi-floor buildings with multiple stairwells.

FED is a measure of exposure to hazardous conditions an individual occupant has encountered. It is dependent on total exposure time and concentration of various asphyxiates or toxins, usually including carbon monoxide, hydrogen cyanide, smoke and heat. FED is calculated as follows [5]:

$$FED = \frac{Dose\ Received\ at\ time\ t\ (Ct)}{Effective\ Dose\ (Ct) required\ to\ cause\ incapacitation\ or\ death} \tag{1}$$

When FED = 1 then the occupant can be assumed unconscious or dead and either way they will not be able to continue evacuation without assistance. If the total FED resulting from a steered simulation was lower than for an un-steered simulation then the steering would be described as successful.

It should be noted that the word “safety” is often used interchangeably with the inverse of “FED” throughout the remainder of the thesis when discussing the results of simulations in a quantified manner. For example if a steering method is said to have resulted in increased evacuation safety then this is referring to decreased computed FED levels.

The remainder of this chapter introduces various aspects of an intelligent egress system including indoor occupant localisation, route planning algorithms and methods of conveying appropriate information to occupants with regards to how they should proceed during an evacuation. Associated technology that would need to be in place to validate assumptions made throughout this project is also discussed. The chapter finishes with a description of previous works that have proposed various incarnations of intelligent egress systems and how they differ from the methods presented in this project, before the final goals are stated. All figures presented in this chapter were taken from previous works and used as an aid to describe and discuss such works. The author of this thesis takes no credit for these figures and each one is referenced appropriately.

1.1 CRISP Egress Model

The egress model CRISP forms a vital part of the project and is constantly referred to throughout the thesis and therefore will be presented here before proceeding any further. CRISP (Computation of RISK Indices by Simulation Procedures) [6] is a Monte-Carlo based model that encompasses all aspects of a fire scenario and was designed primarily for risk assessment. Sub models are employed to represent all physical parts of the environment such as alarms, people, rooms, doors and many more. The fire aspect of CRISP is based on a two layer (hot and cold) zone model of smoke propagation throughout multiple rooms. This is combined with a complex model of human behaviour which includes various types of interaction with the fire event.

Validation studies are necessary for ensuring that an egress model is a realistic representation of a real event. One such study for CRISP was performed by comparison to a trial evacuation of a 3 storey office building [7]. After the trial, questionnaires were given to staff to acquire information regarding occupants' whereabouts and roles at the time of the alarm, to allow creation of an accurate model within CRISP [8].

A zone model has several advantages over computational fluid dynamics (CFD) related techniques when it comes to fire modelling, although these do come at the expense of detail. For use in an intelligent egress system, where lead times will be small, use of a zone model is more appropriate, thus making CRISP an ideal tool for this purpose. Zone models give advantages such as lower demands on computational resources and increased flexibility afforded by being less affected by precise initial conditions that may not be known to the required degree of accuracy.

Each room defined within the building geometry has a tenability rating from 0 to 5 [4], which depends on a number of factors including temperature, smoke density and the presence of various toxins. Vents are used to represent means of moving between rooms and can include windows, doors and open archways. Each vent will have a "transversal difficulty" which can be different depending on direction of travel, as in it is easier to escape a room, which is smoke affected, than to enter one. This vent travel difficulty is directly related to the tenability rating of each adjacent room and results in the term degree of difficulty (DOD) from 0 to 5 [4]. A DOD of 5 is deemed to be impassable under all circumstances and includes windows on the 2nd floor or higher. On the other hand a normal door in safe conditions would have a DOD of 0. To define how occupants move within a room a contour map is created which takes into account all objects and possible obstructions in the room [4].

Occupants within CRISP will always be assigned an action (although this may be a non-moving action such as sleeping, trapped or being unconscious) which is determined by their behavioural roles, which can be naturally occurring or due to specific training, as well as the surrounding environment [4]. Examples include escaping, rescuing others, warning others or fighting the fire etc. Each action requires a certain amount of time to complete and can be abandoned if too much time is required or if the conditions deteriorate sufficiently. Decisions are made based on the knowledge of the individual occupant at a certain point in time, which can often be limited or wrong [4] and route planning takes into account DOD and tenability levels as well as population density. Details of a person's action will affect their posture and thus the actual height their head is above the floor which will affect how likely they are to inhale toxic gases in the hot layer of the zone model. Fractional equivalent dose (FED) is the measure by which risk to life and injury are defined.

Some occupant types more likely to carry out certain actions, than others for example in an office building, an occupant who is defined as "employed" is more likely to search the building, ensuring everyone is alert to the situation than someone who is defined as "unemployed". Moreover, the general occupancy type can be defined as "domestic" or "office" among others. When this option is set to "domestic", each occupant who is carrying out the action "warn others" must do so with each individual occupant [4]. On the other hand, with "office" an occupant who was warning others would only have to enter a room with un-alert occupants to prompt the un-alerted to halt their previous action to begin warning others around them.

When the model calculates a route from one compartment to the next, all vents are initially examined [4]. For each of these vents that are of sufficiently low DOD, when considering the current action of the occupant, the room that the vent leads to is added to a list which includes the required travel distance and this process continues until the target room is reached. However, this relatively long process is usually unnecessary as the route details for each room are pre-calculated, and the routes only require calculation mid-event when vents and rooms become affected by smoke [4].

When used for risk assessment, CRISP is run in Monte-Carlo mode, by which many repeats of similar scenarios are simulated with certain initial conditions being randomised for each individual run. These include initial fire location, initial burning object and initial population distribution, among other lesser factors. However when used during this thesis, CRISP was used to represent a single real evacuation event and some randomisation aspects of the Monte-Carlo model were not exploited. Several sets of initial conditions were used for each case study but some starting conditions were controlled rather than randomised.

Details of how movement speed is affected by population density are hardwired into the CRISP model. However, these were not used for calculating how this affected flow speed in the DRPS to conserve as high a degree of realism possible, while using CRISP to represent real life scenarios. Instructions regarding how to use CRISP can be found in the user manual.

There are many other egress models available, each with their own strengths, weaknesses and specific aims. Most models are validated by the use of real world data. Two egress models were tested and validated by comparing a trial evacuation of an industrial premises with the models' predictions [9]. A range of egress model categories was described where the three different types were:

- Optimisation Models - These take little account of human behaviour and assume that the population will perform egress efficiently. An example of this type of model is ECAVNET+ [10].
- Simulation Models - Focuses more on behavioural aspects than optimisation models. Examples include EXIT89 [11] and buildingEXODUS [12] which was used in one of the key projects [13] discussed later.

- Risk Assessment Models - CRISP

Details of a broad selection of different egress models are described in the following review studies from Kuligowski [8] [14]. Due to the fact that this project was funded by BRE, where CRISP was developed, no alternative egress model was used.

1.2 Sensor Linked Predictive Fire Modelling

Sensor linked fire prediction is an important aspect of an advanced intelligent egress system as the extra information available would allow the future safety of an egress route to be estimated, thus permitting more informed route selections to be made. Such a system, K-CRISP [1], was based on the zone model aspect of CRISP, was developed with the goal of aiding emergency response. K-CRISP has the ability to predict structural failure which provides an advantage in practicality over techniques involving more detailed computational fluid dynamics (CFD) models [15].

Previous works related to the use of fire simulating techniques, together with real life full scale tests had primarily involved the use of CFD [16]. "Blind" models where no sensor data was utilised, confirmed the magnitude of the difficulties associated with predicting how a complex fire scenario would develop. This is evidence for the importance of live sensor readings if useful predictions are to be generated for any realistic environment. Further evidence [17] [18] shows that even for well-defined burning of individual items it is difficult to obtain good match.

The model was steered by live measurements from building sensors which would limit the parametric space for which new simulations are created which form the basis for predictions about the evolution of the fire. Many possible scenario permutations can simulated much faster than real time, even with complex environments, by use of high performance computing (HPC) resources [1]. This accumulation of sensor data allows learning about the fire and as the scenario evolves, predictions may have a greater degree of accuracy. Direct information from some dedicated sensor varieties can also be very useful in producing accurate predictions. An example of this would be if sensors relating directly to the open/close state of a door were in use, the likelihood, and extent of, smoke propagation would be much easier to accurately define [15].

Data obtained from the Dalmarnock fire tests [16] was used to simulate a real time fire and K-CRISP would attempt to predict the evolution of the scenario by directing the CRISP zone model. Various snapshots taken from the publication [15], of results from the simulations are shown in Figure 1-2 to Figure 1-4 where Figure 1-1 represents the symbol key to the following graphs and the time in seconds indicates time from detection [15]. The grey lines represent the outputs of the simulations used to obtain the final prediction. Long term predictions were unsurprisingly lower in confidence than near term estimations.

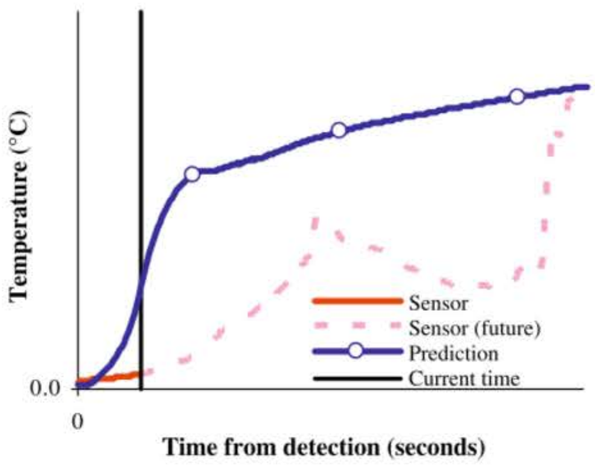


Figure 1-1 - Key for following diagrams [15]

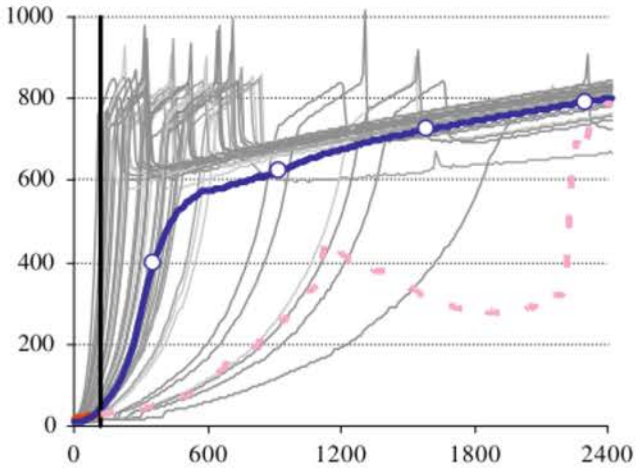


Figure 1-2 - 120 seconds [15]

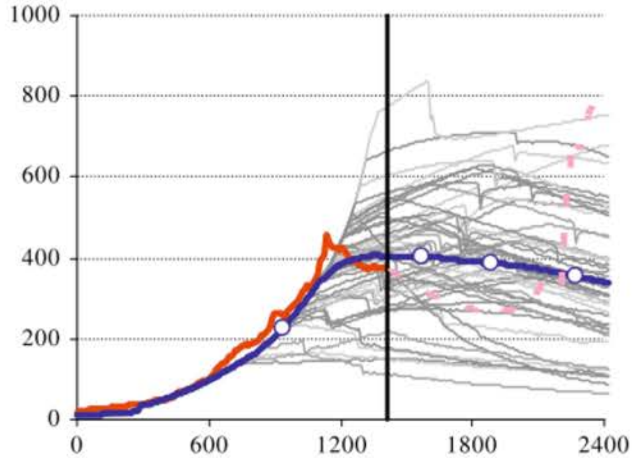


Figure 1-3 - 1410 seconds [15]

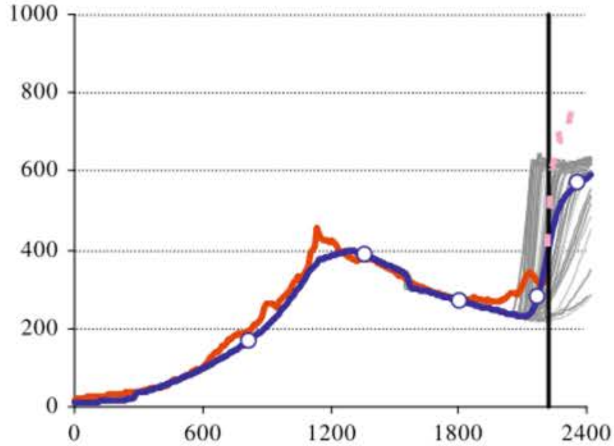


Figure 1-4 - 2220 seconds [15]

The predictions capabilities provided by this system played a part in the FireGrid project [19], where the goal was to aid emergency response by making predictions about whether the situation within certain building compartments was likely to change. For example whether or not flashover was expected to occur or whether any serious compromise in structural integrity was likely. These predictions could notify fire fighters whether or not it was safe to enter a compartment or section of building or at very least aid the decision making process. The project fulfilled its primary goal by establishing that the proposed FireGrid architecture was capable of providing real time information to aid decision making [19], with the system's various hardware and software aspects integrating perfectly.

Similar techniques can also be used to give emergency responders a better idea of what they may be confronted with inside a building in less severe circumstances. An example where the likelihood of fatalities at different locations within a simulated care home is estimated [20]. This information could increase the effectiveness of any search and rescue mission launched by fire services by allowing certain areas to be prioritised.

The hypothetical care home (Figure 1-5) consisted of 33 rooms with an elderly resident in each of the 20 bedrooms and 2 staff members on night duty who were assumed to be initially located within a staff room (room 28). Each room is fitted with a smoke detector. 25% of the elderly occupants required assistance to escape and would have to await rescue after being alerted by the alarm. The remainder were able to evacuate without assistance. The simulated fire in this case started in room 25 [20].

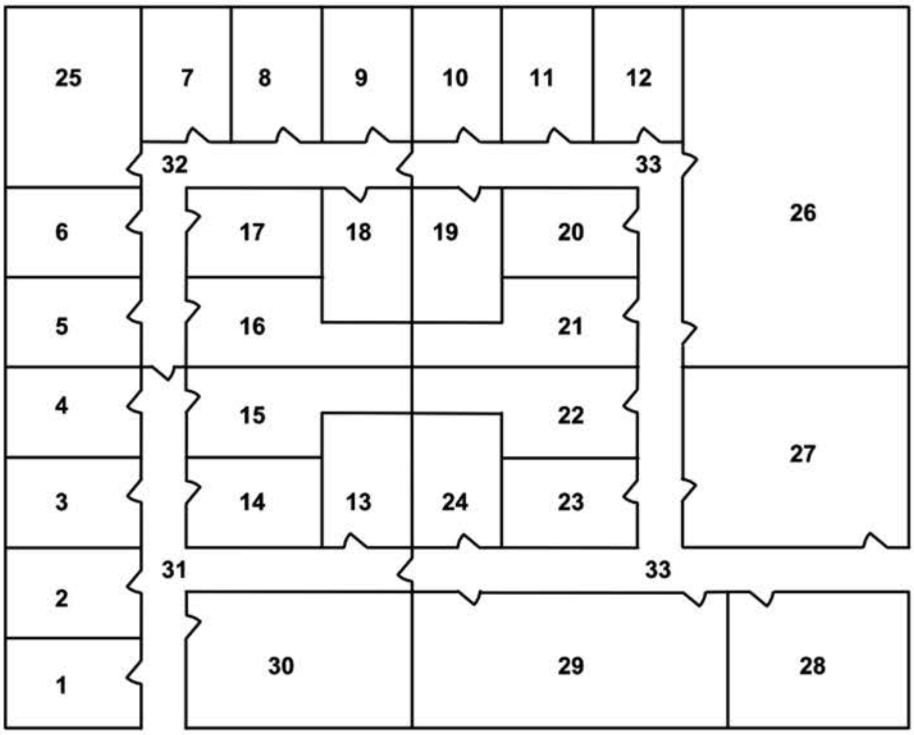


Figure 1-5 - Care Home Layout [20]

Figure 1-6 shows how the scenario has progressed after 5 minutes, with orange highlighted areas representing compartments in which a detector has been activated. If a room has a skull indicator then a fatality has been predictor to occur at this location within 30 minutes of the fire starting. A visualisation akin to this could be a useful tool for use by emergency rescuers in determining the tactics for their search. However it gives no indication of the degree of the risk posed in each compartment nor does it show where occupants have been deemed to receive a near lethal FED dose as they would also likely be in urgent need of rescue. In an environment such as this care home, it would be advantageous if the system would know exactly which bedrooms belong to occupants that were in need of rescue, as this could affect the results of the super-real time modelling.

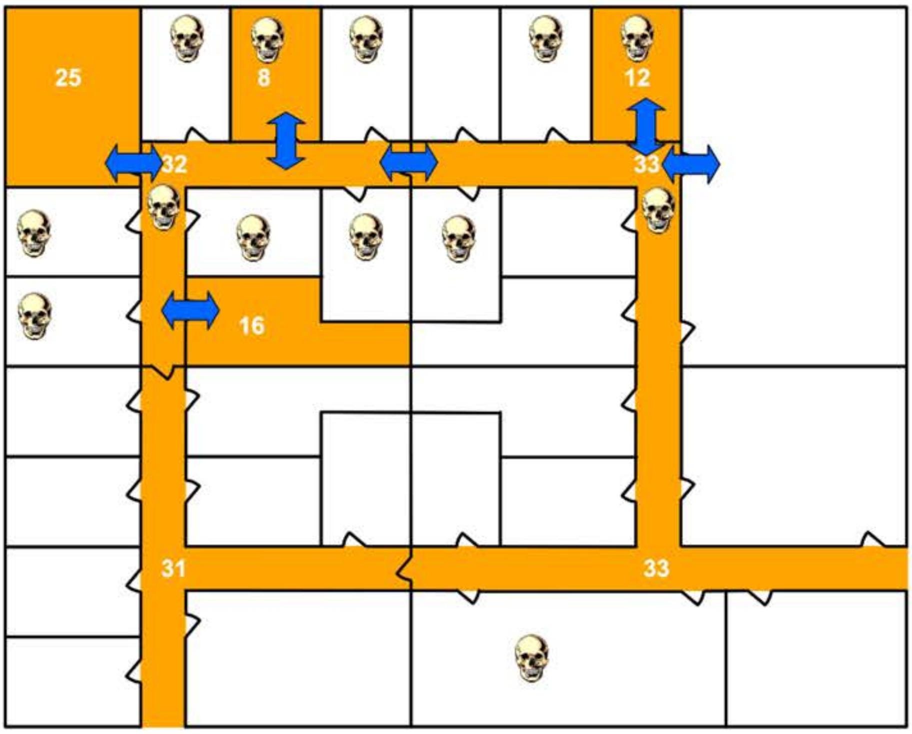


Figure 1-6 - 5 minutes after ignition [20]

A closer look at the results showed that a significant majority of predicted deaths occurred within the sections of corridor [20]. It was unknown whether this could be attributed to the actions of staff members attempting rescue but it was noted that if the staff were removed from the scenario the number of deaths was higher and over a greater range of locations.

An important consideration in this field is the possibility of sensor failure. Thermocouples are designed to handle temperatures in excess of 1000 centigrade [15] but failures do still occur. For this reason it is imperative to be able to screen data for anomalous results which could otherwise lead to the generation of nonsensical data and thus erroneous predictions. In this case, the scope of reasons for which a sensor could return a flawed result is limited to being out with a certain numerical range. Therefore if a temperature reading is out with a lower and upper threshold then it could be excluded automatically.

As the dynamic route planning system proposed in this project is founded upon assuming the actions of occupants, this study provided a base for which key ideas in this project were built. Similarities include the use of modelled sensor data to provide input parameters for use in faster than real time egress simulations which in turn provide useful information for end users. The other studies mentioned in this section dealt specifically with predicting the evolution of the fire, while being an important aspect of assisting in evacuation, the associated uncertainties are significant. A significant conclusion that can be drawn from these works is that live information about the state of a hazard can be successfully interpreted by sensors and utilised for improved real time planning of egress routes.

1.3 In-building Occupant Localisation

For the system developed in this project to function, knowledge of occupant location is crucial. This is possible using smartphones but not by using the standard GPS related methods which struggle to operate with any accuracy in the built environment. A novel method for such smartphone indoor localisation using a combination of "dead reckoning and Wi-Fi signal strength fingerprinting" was proposed by Kothari et al [21]. Other methods of using inbuilt smartphone technology to determine location are also available and these will be discussed before the more promising techniques.

The use of a Bluetooth capable device to determine occupant location has been experimentally evaluated across a range of indoor scenarios by Feldmann et al [22]. An assessment of the position of the device is achieved by using signal strength measurements and a combination of triangulation and least square estimation [22]. The empirical tests in this project showed that position estimates were precise to 2.08m (Route Mean Squared - RMS) [22]. The dynamic route planning system proposed in this thesis assumes knowledge of occupant location to room or compartment level, therefore the estimates discussed here would be considered accurate enough for an intelligent egress system. However there are drawbacks in that the maximum distance possible between the device and access points was 8m. If such a system were to be installed there would be a substantial hardware requirement and therefore expense. The use of the standard integrated camera which now feature on the majority of phones to determine occupant location, has its advantages, according to Se et al [23], but there are too many drawbacks for it to be practical for use in such a system. For example, this would require the user to be actively using the camera at very regular intervals. There are also uncertainties relating to the settings on the camera and changing environmental light levels [21].

Dead reckoning (DR) can utilise components of smartphones such as the gyroscope, accelerometer and magnetometer, giving accurate and timely estimations of occupant position, according to Steinhoff et al [24]. There are however drawbacks to using DR as a standalone method, especially when travel distances are substantial as without being seeded with an initial occupant location from another data source, the errors are unbounded and DR data will be rendered redundant. This is why Wi-Fi signal strength is also used, although this alone produced more inaccurate results than only using DR. Using a combination, however produced a mean error in location of roughly 5m, which is accurate enough for use with an intelligent egress system. The advantages of such a system are that it will be possible to track how a person moves rather than simply the number of occupants at a discrete location and their additional hardware requirements over and above the smartphone are limited to the provision of Wi-Fi throughout the building. As the specific identity of the person is not required, there are fewer privacy issues with such a system.

Radio Frequency Identification (RFID) provides another potential method for occupant localisation in the built environment. A feasibility study into the use of

RFID bands on the wrists of hospital patients and staff was explored in a recent project at The University of Edinburgh by K. Post [25], where interviews and questionnaires were carried out with members of the public, fire service and medical personnel. The result of this study was that use of such occupant tracking methods would be widely accepted [25] and that it would therefore feasibly form part of an intelligent egress system. It is clear that if the technology discussed in this project could be used in a wristband, that it could easily be used in name tags displayed on one's chest that could be made compulsory in certain public buildings.

The benefits of integrating RFID technology with building information modelling (BIM) in terms of increasing the precision of RFID localisation has also been investigated by Costin et al [26]. The addition of BIM techniques significantly reduced the number of false reads compared to RFID alone as well as achieving a best case accuracy of 1.66m [26]. As the original goal was to achieve a maximum error of 3m (Taneja et al [27]), this study proved successful. This is clearly accurate enough to justify the assumed occupant location knowledge for the DRPS knowledge used throughout the project. It can be concluded from the various methods of indoor occupant localisation described here that this area of technology is not a barrier to the concept of intelligent egress. It is envisaged that such a system would be more likely to be installed in a large complex building, belonging to an innovative, forward thinking company. This would negate a lot of possible privacy issues associated with building types that may also benefit from intelligent egress, such as a hotel.

1.4 Egress Route Optimisation

A theoretical approach to route planning in an emergency event in the built environment, the maximal safest escape (MSE) problem, was proposed by T. French [28]. This approach utilised an evolutionary algorithm to attempt to find near optimal flow pattern solutions to stochastic, time varying network of nodes and edges. When a network reaches a certain complexity, it becomes unlikely that a mathematically optimal solution will be found. Occupants were modelled as homogenous, independent units of flow with no individual characteristics or explicit interactions except for the use of shared space.

An evolutionary algorithm produces a base-line solution through random route selection and then attempts to select the parts of the solution (genes) which are the most successful. These more successful genes can then be combined, along with some new ones and the process is repeated a certain number of times or until an accepted success threshold is achieved, while continually updating the ranking of genes. There were limitations in terms of applicability to real situations, such as where occupants were not allowed to wait at nodes. As queuing is likely to be matter of fact in evacuation of any densely populated building this assumption is violating in terms of direct applicability to real scenarios.

Another study, by Garcia-Ojeda et al [29], into route planning during evacuations utilised a similar node-arc network as in French's project. Nodes were used to represent areas that a person could occupy (stairs, rooms, corridors, intersections etc.) and arcs represented the travel paths between nodes (doorways, gates etc.). The goal of the algorithm was to minimise evacuation time for a building. Each location has a capacity representing the number of persons that can occupy a space and passages are assigned a maximum flow rate and total travel time. The major difference from French's work is that waiting at nodes is permitted and the movement of occupants can even be delayed if necessary to avoid evacuation blocking bottlenecks

A novel method for optimising evacuation route selection in real time has been proposed by Cuesta et al [30], where the example building is a single storey factory. The building was broken down into several discrete areas, from which all egress routes were considered. Pre-movement times and walking speeds for each area were varied according to the intricacies of each area [30]. Pre movement times are likely to vary across different parts of an industrial complex due to the necessity of shutting down certain crucial processes that could otherwise create further hazards, before evacuating. The use of ear protection will only further increase pre movement time as alarms may not be detected immediately. Movement speeds for each area are varied according to the presence of movement slowing factors such as narrow sections of corridor or stairwells. It was stated that is also possible to vary these input parameters between different routes from the same area but for the results presented in the publication this was not the case. Therefore as evacuation time was used as the main measurement for success this would imply that the shortest egress route from each working area, if available after considering hazard location, would be highly likely to result in the chosen optimal path.

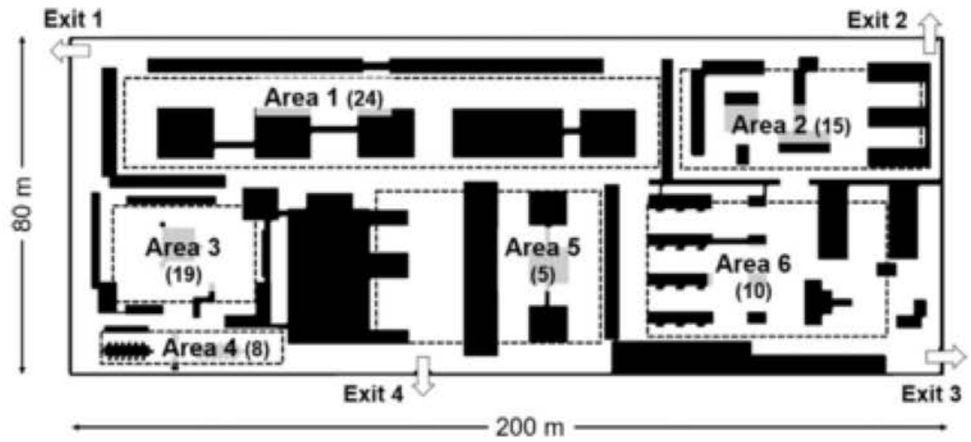


Figure 1-7 - Building Layout in (cuesta et al). Each area has the number of habiting occupants shown in brackets [30].

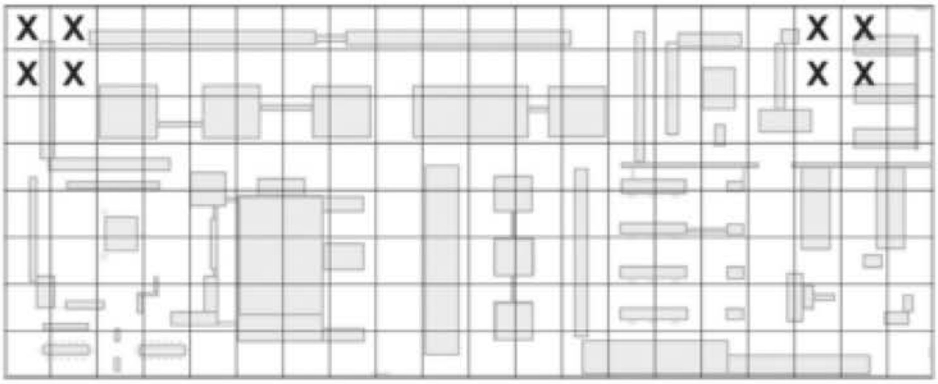


Figure 1-8 - (Cuesta et al) Building Layout mapped on Grid. This GUI is used for the user to manually enter where the hazards are located. The X mark grid squares that can't be used for evacuation [30].

Tests were carried out both with and without emergency situations including those with multiple emergency locations. For each working area a hypothetical normal distribution was employed for each of the input variables and a total of 34 possible evacuation routes were defined [30].

Test 1 was repeated 1000 times and involved no hazard, implying that all evacuation routes were available. Unsurprisingly, the chosen evacuation route from each area turned out to be the shortest path by distance although it is explicitly stated in the paper that this will not always be the case. Test 2 involved 10 different scenarios, each of which was repeated a further 1000 times [30]. As per the results from test 1, if the shortest route was available after considering the hazard location it was selected as the optimal route from each area on every occasion excluding one from working area 1, where the difference in distance between the shortest and second shortest route was only 1m. In the remaining cases, the shortest available route was also selected, which was to be expected as walking speeds were not varied between different routes from the same area. This implies that it is possible to conclude that this system, under such inputs is highly likely to select the shortest safe available route from each area.

One stated limitation of this system is that it has only been designed to handle sparsely populated buildings where crowd dynamics and how population density affects movement speed are not considered. This would imply that occupants initially located in different areas have no impact on each other's evacuation and is further evidence for suggesting that the system will always select the shortest available safe route from each area, while movement speeds remain equal. There are drawbacks with basing evacuation plans on very specific inputted movement speeds for certain routes however, as these are likely to be effected by factors such as temporary changed to building layouts and poorly planned placement of large objects that will impede egress. Another limitation is that there is no automatic hazard detection is incorporated in the system and the location of these must be entered manually by a human controller.

The major differences between the models described in this paper and the topic of this thesis are that the DRPS considers the effect of population density when evaluating solutions and used predicted hazard exposure, rather than evacuation time, as the primary criteria for route selection. At the time of writing the effectiveness of improving evacuation safety has not been tested although results from such tests, be it live or simulated, are eagerly anticipated.

1.5 Methods of Conveying Evacuation Route Instructions

1.5.1 Dynamic Signage

The ability to convey route instructions to the occupants in a manner that is easily followed and understood is a key concept of intelligent egress. The GETAWAY project [13] has undertaken numerous tests involving live evacuations from railway stations, to evaluate their Active Dynamic Signage System (ADSS). The principle of the ADSS is to improve over the standard green running man exit signs by introducing two novel concepts to the original design. One of these is to attract the occupants' attention over and above the original sign (a green, flashing arrow was used in this case) with the other addition being having the purpose of notifying whether a previously available exit route is now no longer recommended. Before the latest set of tests in this project, it had been suggested that the ADSS could successfully instruct 63% of the occupancy to use the target exit. This number however, includes those whose initially nearest exit happens to be the target exit, so they were expected to utilise this exit regardless. When these occupants are removed from the results the ADSS effectively directed 43% of the remaining occupancy [13]. During these tests a voice alarm was also implemented that would instruct the population to their nearest exit.

These signs only included either positive or negative information and when they were adjusted to include both types (i.e. an unusable exit also directing to an alternative) this improved the redirection rate to 49%. Changing the voice alarm instructions to ensure that there was no inconsistency between the signage and vocal instructions, this improved this number to 58% [13].

From these trials, it can be concluded that to improve occupant adherence to egress instructions, important improvements on the standard exit signs can be made by including both positive and negative instructions rather than one or the other. Another more obvious conclusion is that any vocal instructions should not contradict visible instructions. In addition to these tests, participant surveys were also carried out from which there was a contradictory conclusion that more simple signs were preferred by the majority occupants. This implies that when it comes to signage that can display a range of possible instructions, it may be preferential that an alternative to the standard green running man is employed.

Another aspect of the GETAWAY project is to add "intelligence" to the ADSS to create the IADSS [13]. As of the time of writing, this hasn't been incorporated into any live tests akin to those described above and the details of the system are said to be the subject of a later publication. Nevertheless, a basic description of the intended system, along with Figure 1-9, will now be described. The aim is that the system will use CCTV to monitor the number of occupants present, and a variety of sensors to monitor smoke, toxic gases and heat. Many CFD simulations will be run before the system is installed within the built environment to create a library that can be accessed during an emergency scenario. This would allow the real time sensor data to be matched to the most similar fire in the library, akin to the previously described K-CRISP model with the major difference being the use of CFD rather than zone models where the difficulties associated with producing a range of sample fires using CFD models will apply. The population and fire data will then be fed into their egress model, EXODUS [13], which will execute multiple pre-defined egress plans, selecting based on factors such as expected fatalities and evacuation time. An array of possible evacuation strategies are then presented to a human operator who will decide which of these to implement, which will in turn adjust the signage system as appropriate. All of this is to happen faster than real time, before any alarm is sounded. For scenarios with a large number of occupants in a complex building layout, the faster than real time requirement is challenging to meet, especially as it is required to be considerably faster than real time for the purpose described. According to the buildingEXODUS website [31], for a scenario with 8,100 occupants in a building comprising 50 floors, using a 3.3GHz, 8Gb computer, the required run time is 25 minutes. Although this is likely to be faster than, or at least near, real time for a building of this size, it is likely that running multiple simulations as part of the decision making process before sounding an alarm would require too much time.

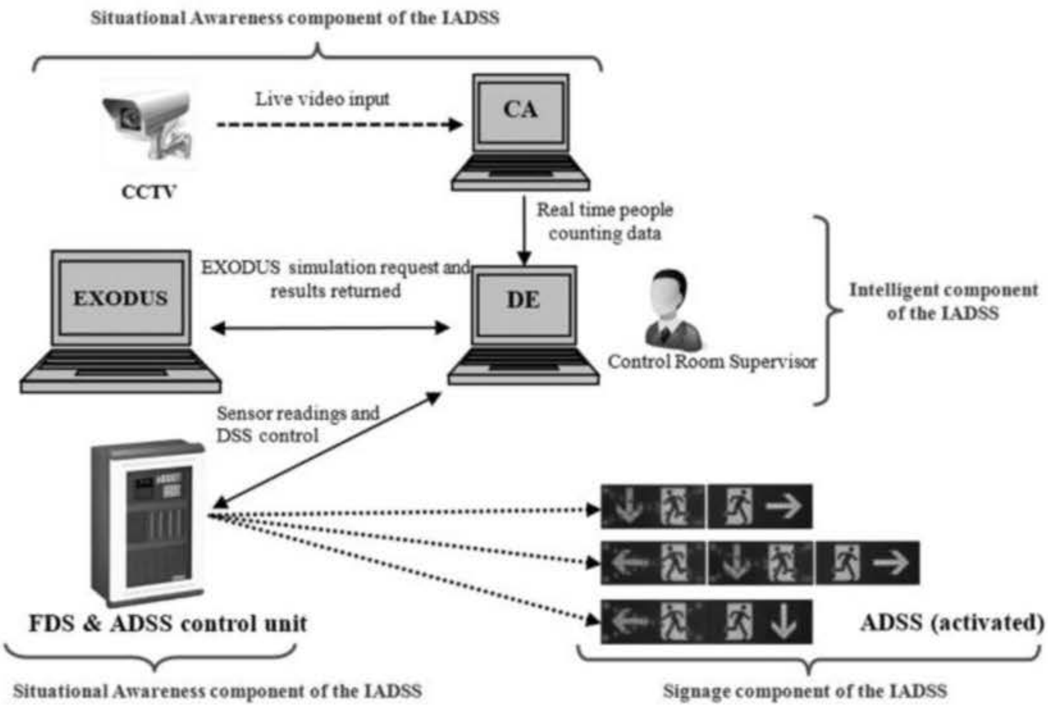


Figure 1-9 - GETAWAY IADSS - System Architecture [13]

The system described in the GETAWAY has many similarities with the one developed in this project but with some key differences. The DRPS presented in this thesis is completely automated and therefore does not use or require human intervention and selects an evacuation plan based on perceived overall hazard exposure. However, there are obvious advantages to using human intervention, in that false alarms or malfunctions/nonsensical results from the intelligent system could be more readily identified and rectified. The disadvantages of a human stage in the decision making process include increased cost, increased time from detection to provision of route instructions and the introduction of human user error, including times where the person may not be at their designated post when an emergency event occurs. It is likely to be a simpler adjustment to include human intervention in an already automated system, than to automate a human driven decision process. For this reason, adding human intervention was not considered during this thesis.

When testing of the full IADSS does take place, it is likely to measure success based on escape route utilisation as per the currently published results. On the contrary; the simulated tests in this thesis uniquely base result success on FED values. The IADSS also intends on using predictive fire models in determining the safest evacuation plan whereas this project does not, although this is defined as an important part of future evolution. The significant difference here is that GETAWAY intends on using CFD models for the predictive fire capabilities which is highly demanding on computational resources and more dependent on specifics of the scenario where the system is deployed. If this system is to be installed in multiple environments there will be significant expense involved in building the required library of fire scenarios for each of these. Subsequently, if any changes to the building arrangement, such as movement of large furniture, partition walls etc., take place after a system has been installed, the pre-run CFD models will be rendered obsolete.

The use of flashing lights to influence exit awareness and choice was also investigated by means of experiments carried out in road tunnels and buildings, by Nilsson [32]. One aspect that was also explored by Franztich et al [33] was how walking speed is affected by differing levels of light extinction coefficient in smoke filled tunnels when different guiding tools are used. In this case an infrared thermal imaging camera was used to record the evacuees' actions throughout the experiment. Unsurprisingly, increased smoke density and increased extinction coefficient resulted in decreased evacuee movement speed although being adjacent to a wall allowed faster movement than otherwise and ultimately the smoke density reached a certain level, the only movement was along the walls. More surprising was the apparent ineffectiveness of the flashing lights and lines painted on the floor [33]. The painted lines were white and their visibility may have been compromised by the use of fake white smoke.

A key finding from this experiment was that when people attempt to escape by "hand-railing" a tunnel wall, they often fail to notice an emergency exit on the opposite side of a tunnel. The consequences of such actions could be catastrophic and it is highly plausible that similar phenomena could occur within the corridor of a building, if it were of sufficient width. The suggested solution to this issue provided in the study was to implement signage as per Figure 1-10 where there is an alcove opposite the actual emergency exit. This would be more difficult to miss for evacuees who were following the tunnel wall opposite the intended exit.

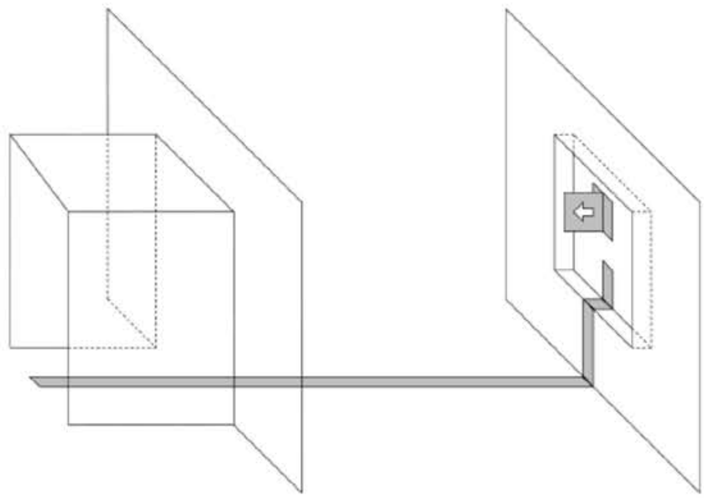


Figure 1-10 - Tunnel Emergency Exit Signage [33]

The influence of different types of light upon choice of egress route was also investigated, this time in a building rather than tunnel, as well as the effect of varying the colour of the light [34]. The results showed that flashing or strobe lighting significantly increased exit utilisation when compared to the standard green emergency exit sign. This result is in line with what was discussed previously [13]. It had been noted in a previous study, by Seike et al [35], to the one being discussed that blue flashing lights were deemed effective due to the colour blue's association with the emergency services. However, this was contradicted by this experiment which concluded that green was the optimal colour for use in emergency flashing lights.

Orange and red lights were also tested but unsurprisingly these proved ineffective. A further experiment by Nilsson et al [36]; where uninformed occupants were involved in a trial building evacuation, reinforced the effectiveness of green flashing lights next being used to highlight emergency exits that would not be used under normal conditions while also suggesting that they should only be activated during an event requiring evacuation.

1.5.2 Personal Devices

An alternative to changeable signage is now discussed. The novel idea of using a phone app to improve safety in fire emergencies in the built environment has been proposed by Barden [37]. The concept of EvacApp [37] was developed at the University of Edinburgh, which was designed to be an opt-in system that would be installed on a user's smartphone upon entry to a building. Upon the commencement of an event requiring an evacuation, the app would activate automatically while being capable of determining the location within the building of the occupant using inbuilt smartphone technology. It was assumed that any building where such an app would be utilised would provide Wi-Fi throughout. Appropriate route selections that have been determined by integration with a range of possible intelligent systems, can then be conveyed directly to individual occupants. To avoid the well-known phenomena of reduced walking speed while looking at a phone screen it was suggested that instructions could be vocal. However there seems to be flaws with this idea in that multiple vocal instructions from phones in close proximity could hinder occupant's understanding of the directions. Moreover, it is possible to assume that in a scenario where specific route choice is crucial to safe evacuation, successful interpretation of the instructions is of greater significance than walking speed.

Several different grades of EvacApp were proposed [37] depending on the available systems to integrate with. Grade 1 would comprise knowledge of the building layout, occupant location and whether or not an emergency had occurred. No specific knowledge of the hazard was included here. This grade would have the potential of reducing pre-movement time and improving utilisation of purpose built emergency exits as the likelihood of an occupant simply following their original route of ingress is reduced. However this would not be suitable for exploiting the full potential of intelligent egress, for which knowledge of the hazard location and severity is necessary, which is what the grade 2 version of EvacApp would allow. Grade 3 would is said to include a FireGrid style system incorporating route decisions derived from predictive fire data.

Whether or not people would be interested in using such a tool to aid egress or if the app would be trusted make possibly survival dependent decisions is a significant topic of discussion. An example of a situation where smartphone app technology is used trusted in such situations is in determining the blood sugar level of people with type 1 diabetes. A large part of this project was involved in carrying out surveys and interviews to determine the feasibility of the app being employed in a real environment [37]. It was concluded from this investigation that a need for such an app exists and that the technology would be trusted to some extent [37]. Such an app could prove very useful in any future intelligent egress system as the use of a smartphone would aid in occupant location monitoring and even identity, where ethically sound and where required. As opposed to changeable signage, this technology would allow the instruction of occupants on an individual level where suitable. For example, it may be optimal to direct half of a group to a different exit from the other half, to reduce congestion.

Another project at The University of Edinburgh (Onwueke [38]) aimed to further develop the concept of EvacApp by testing a simple app that would show ones location on a particular floor of a university building. This app used the device's accelerometer, gyroscope and compass to determine occupant location. A survey was carried out on what people's thoughts were on using such an app for evacuation, which takes the surveys from the EvacApp project one stage further by allowing users to get a feel for app aided evacuation before responding. Conclusions from the surveys showed that 92% of users were satisfied in the app's ability to show their location but only 58% would trust the app in a real life scenario [38]. A common point of view shared among the interviewees was that such an app should never fully replace existing detection and alarm systems. As detection systems are required for the concept of intelligent egress to exist at all this is unlikely to ever occur.

App aided evacuation has also been explored in other parts of the world although test results have yet to be seen, from Wu et al [39]. Using Radio frequency identification for location monitoring and the integrated smartphone compass to determine orientation, it was possible to guide evacuees in the correct direction using a simple coloured arrow [39]. Different coloured arrows were used to represent proximity of the hazard (Figure 1-11). Such a simple interface and fool proof instruction that would work in poor visibility are an interesting idea but more information about the proposed system behind the app is required for a more in depth assessment.

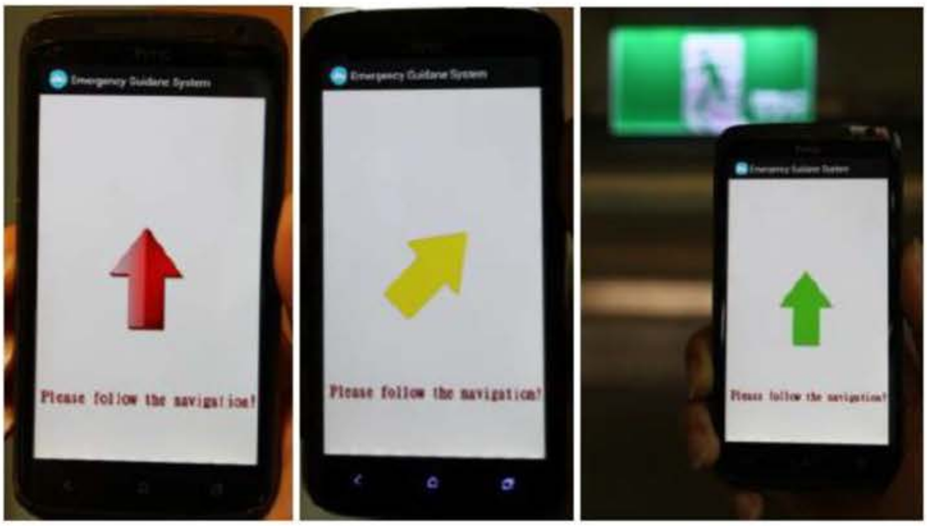


Figure 1-11 - Navigation using proposed app. The red arrow represents closer proximity to the hazard [39].

The next stage in this area of research would be to demonstrate integration with a fire detection system. At the time of writing, app aided evacuation has potential in that it allows, by default for the location of a smartphone carrying occupant to be known to a reasonable degree of accuracy, without effecting privacy.

1.6 Previously Proposed Systems

An earlier feasibility study designed to demonstrate how an intelligent egress system would work was carried out by Grindrod [6], using CRISP to represent a large multi-floor building, based on the 12 floor Britomart East Building in Aukland. Figure 1-12 and Figure 1-13 show the floor plan used to represent each level of the building. The simplification of the floor plan CRISP model eased the difficulty of building input as well as reducing the likelihood of issues with the zone model occurring.

The goal of this study was to determine if it were possible to influence occupants' choice of stairwell by use of way finding tools installed within the CRISP code. These modifications consisted of adjusting the degree of difficulty attributed to each vent that connects the habited floor space, with the affected stairwell.

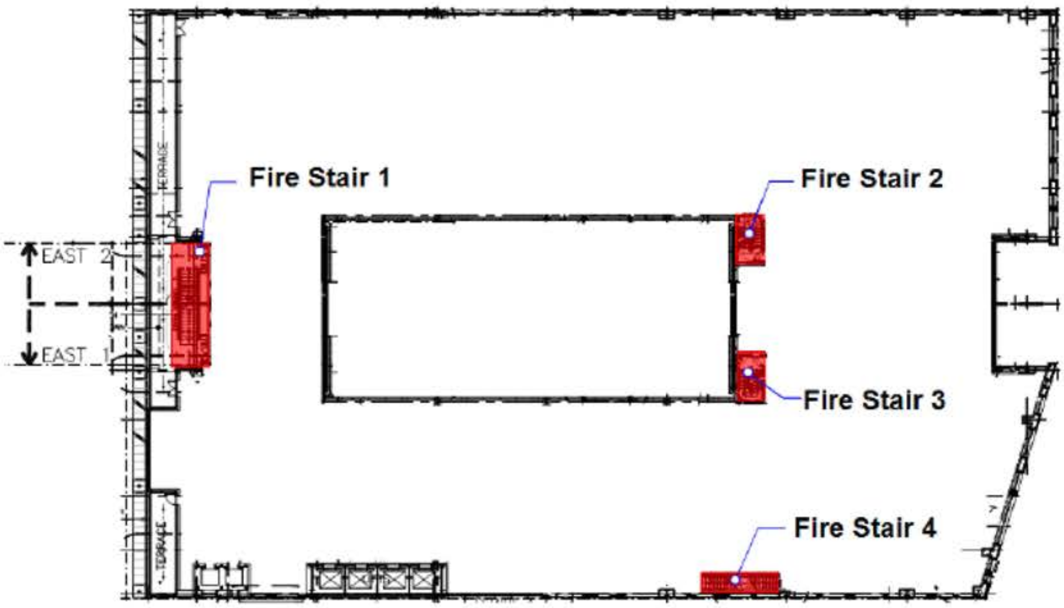


Figure 1-12 - Building Floor Plan [6]

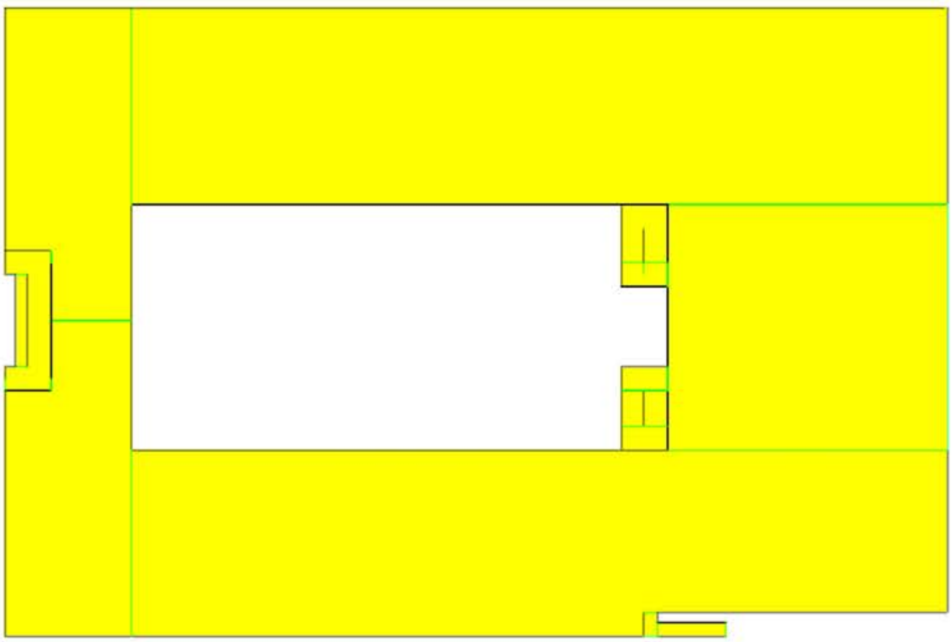


Figure 1-13 - Simplified CRISP Floor Plan [6]

A series of scenarios, including a hazard-free base-line scenario and ones deemed "worst case" where one or more stairwells were declared unusable due to smoke were tested with and without the additional CRISP modifications. The nature of how the hazard was actually generated within the model, was not stated. There were slightly over 2000 occupants initially inside the building spread across the 12 floors. Measurements were made relating to stairwell usage, overall evacuation time and occupant flow rate.

Results showed that the base scenario resulted in the quickest overall evacuation, unsurprisingly due to all four stairwells still being in use. Occupant flow rate in this case had no independent value as it is inversely proportional to overall evacuation time and will not be considered for further discussion.

As a result of the specific method of dissuading occupants away from utilising the effected stairwells during simulations where this was being employed, no occupant would ever attempt to enter one as it would violate the human behavioural rules within CRISP. This implied that 100% obedience to the system was assumed as during scenarios with affected stairwells where the system was not running however, a number of occupants would attempt to use this stairwell. Scenarios where the system was not in use would have been expected to be slightly quicker overall due to the small number of occupants using the compromised stairwells, but this was not always the case. This is most likely attributable to which specific stairwell is smoke affected and how many occupants will have direct line of sight with the vent that leads to this stairwell. Another factor is how quickly the occupants can recognise that a stairwell is unusable and as the system increased the DOD to its maximum value, this is likely to allow faster perception. Due to the way CRISP operates, if vent attributes are changed during a simulation then any routes involving them will be saved as normal. If occupants can change their route at an earlier stage then less time will be wasted travelling to an unusable stairwell.

The way finding tools that were implemented in CRISP, in the discussed project, did achieve their goal of influencing stairwell choice but due to the involved method, this was a certainty. Evacuation time was the other measurement by which success was defined where it may have been beneficial to consider FED values as there would be some non-zero values for this for scenarios where the system was not operating. A comparison of FED values between influenced and non-influenced simulations would give a better idea of the effectiveness of the system in improving safety. The current thesis makes the following improvements and changes when compared with the discussed project:

- Sensor data was used by a separate dynamic route planning system to automatically generate evacuation plans, rather than manually defining the DOD of the entrance to each stairwell.
- FED was used as the defining factor for evacuation success, as opposed to route choice or total egress time.
- The system was tested in more complex and challenging scenarios.

Buildings of significance regarding their architectural heritage provide a unique challenge for achieving safe egress. This is down to the combination of wanting to protect high value interiors, a building layout that will have been conceived with no thought for fire safety and a generally unfamiliar occupancy. A recent study by Bernardini et al [40] investigated employing intelligent evacuation principles in an Italian theatre, while having minimal visual impact on the architectural properties, with many aspects similar to that of this project. Simulated evacuations were used to represent the real building which was divided into several control areas. This system also depended on sensor data to gather information about occupant localisation as well as a fire detection system. Each discrete building zone would have a defined maximum population density, which when reached or exceeded would result in the system directing occupants along alternative paths. The method by which occupants were instructed was via changeable floor lighting and signage. Once again, total evacuation time was used as the defining factor for success and in this case it was achieved. The implemented system reduced evacuation time by a total of 26% [40]

when all levels of the theatre were considered. This very recent study has a lot in common with the current project, but had not been published by the time this thesis project had begun. There are however key differences, the main one being that the Italian theatre study uses time as the definition of success whereas this project uses FED. It also appears centred on a more heuristic approach using decisions based on limiting occupant density than the multiple solution evaluation presented in this project. At the time of writing this appears to be the most promising and closely related study yet discovered. It is more closely related than Grindrod's work, despite not using CRISP to represent the real environment, due to the proposed system making decisions based on occupant densities as well as hazard location, both obtained from sensor data. The system is also far more complex than that proposed by Grindrod.

1.7 Project Aims

The goal of this project is to build on the strengths of several previous works. Using CRISP to represent the real environment and comparing influenced and non-influenced evacuation as per past studies [6] will form the main part of the project. Novel aspects of this project will be the use of a dynamic route planning system to generate evacuation plans based on simulated sensor data to directly steer the occupants by a more realistic method than previously used. The use of FED as the measurement for evacuation success and safety, with regards to sensor steered egress, is the other key novel contribution.

The main aim of this project is to demonstrate the potential benefits of an intelligent egress system, through the use of simulated evacuations and to demonstrate that influencing occupants' egress routes results in lower overall FED values. The requirements for the generation of evacuation plans that will be used to instruct occupants are as follows:

- The plans must be produced in near-real time for purposes of practicality when used in a real environment.
- The system should require only modest computational resources.
- Sensor data should be conservative to the point where the assumed knowledge of the system is clearly within technological capabilities.

In addition to these, how the method of steering and DRPS sophistication impact on the effectiveness of the system is also to be determined. The specifics of the scenario in which different aspects of the system have the greatest potential benefits were also explored, therefore allowing future recommendations to be suggested. It was initially hypothesized that as the scenario becomes more complex or hazardous, the greater potential benefit to life safety, such a system could provide.

2 Intelligent Egress System Structure

The foundation of the intelligent egress system is the ability to generate effective, efficient evacuation plans in real time, which are appropriately adjusted to the precise scenario at hand. Sensor data related to the evolution of the hazard and occupant location and behaviour has been used by a Dynamic Route Planning System (DRPS) to produce suitable evacuation plans, in real time, that could be conveyed to the occupants using a variety of methods. The DRPS described here was developed in its entirety during this project, by the author, and was designed to form part of a coupled system in which the egress model CRISP would be used to represent a real fire scenario. CRISP and the DRPS are separate programs which interact by sharing data files. Sensor data is sent from CRISP to the DRPS and route instructions are sent the opposite way. This chapter describes the details of the methodology for each component of the DPRS and adjoining Intelligent Egress system used throughout this project. Details of modifications to the CRISP model that allow for the coupled system to operate are also included. The full system architecture is graphically displayed in Figure 2-1.

Hazard, occupant location and alarm data is constantly monitored and interpreted to determine if an evacuation is required. If it is deemed necessary then all data for available paths from each populated area is retrieved, the safest of which is selected for solution generation. All solutions are then evaluated for overall safety and evacuation time with the safest or fastest equal safest solution being chosen to influence occupants. Predictions of how occupants will move throughout certain parts of a building can be improved by monitoring how movement speed is affected by population density, by using previously accrued data.

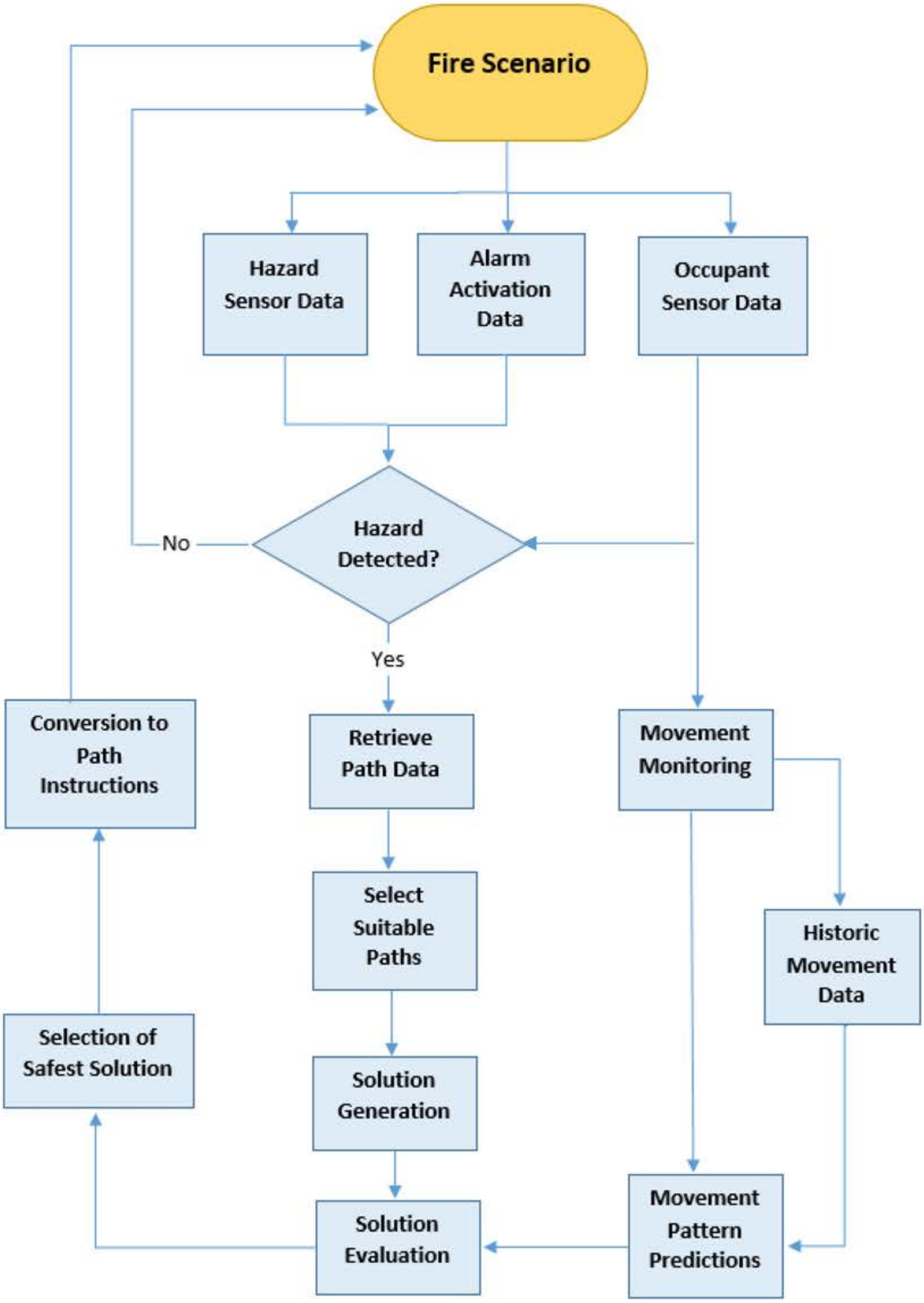


Figure 2-1 - Architecture of Intelligent Egress System

2.1 DRPS Node Edge Network

In the DRPS, the built environment is represented by type of node – edge network. Nodes represent areas where occupants inhabit, such as a room, corridor or place of safety out with the building, and points on a path where decisions are required such as doorways and corridor intersections. Edges represent the travel between the centre-point of each node, although an occupant is always occupying a node regardless of their exact whereabouts. The examples in Figure 2-5 and Figure 2-6 consist of a network of 61 nodes. Figure 2-2 shows an illustration of part of the node network and how it relates to the equivalent building layout in an example CRISP simulation.

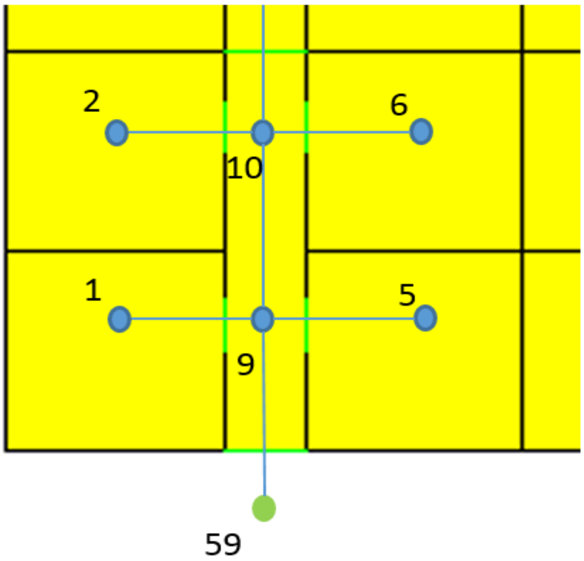


Figure 2-2 - DRPS Node network overlaid on part of example CRISP simulation. Green node 59 represents a place of safety (outside building)

2.1.1 Nodes

The DRPS stores the following attributes about each node:

- Identifier – Defining node number (integer).
- Name – A string which refers to the node number (e.g. “node_1”).
- Safety – Boolean referring to whether or not the node is a place of safety.
- Number of adjacent nodes.
- Adjacent nodes – List of identifiers for each adjacent node.
- Length of edges – List of distances to the centre for each adjacent node.
- Distance to next node along edge – Distance, from centre of current node, along each edge that is required to be travelled before area within adjacent node is reached. Illustrated in Figure 2-3.
- Dead end – Boolean referring to whether or not node is a dead end (e.g. a room with only one entry).
- Hazard sensor number – Which room sensor refers to this node (as each network node might not refer to the equivalent room in CRISP).
- Working area – This is a user estimate of the relevant available floor area when calculating movement speeds for travel within the node. An estimate is used as the entire floor area of the room is not always appropriate when calculating movement speeds within a node as the area around a door/exit is where the majority of the occupants will be while trying to escape. For example: Two rooms which are similarly shaped, each with a single exit, but with one room being larger than the other, are likely to have the same working area because of having equal space around the door. The working area of a corridor is taken as equal to its entire area. Justification for the use of an estimated value is that these were intended to be adjusted automatically when perpetual occupant movement monitoring (section 2.5) is employed.

This would mean that if the initial estimates proved to be significantly, systematically wrong, then lower FED results would be expected from tests that employed this feature of the system.

The nodes each require manual input to define the network. An example node, which refers to the room at the bottom left corner of the building example in Figure 2-2, is shown:

```
node1 = Node(1, 'Node_1', 1,  False, 1, [9], [3], [2], [1], 4)
```

When the node network is created to represent a multi-floor building, it is necessary to define which nodes represent stairwells. In addition to this, it is also necessary to define a list of key nodes for each floor, which will usually represent each exit and stairwell. This is to ensure that a diverse range of paths is generated - described below.

2.1.2 Edges

The edges within the network are generated automatically from the node details and have the following attributes:

- Identifier – Defining edge number (integer).
- Name – A string which refers to the nodes which this edge connects (e.g. “edge_1_9”).
- End nodes – The nodes which this edge connects.
- Edge length

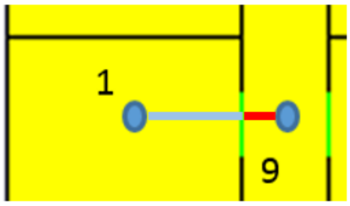


Figure 2-3 - Node break illustration showing "edge_1_9". The node location changes where the colour changes along the edge.

2.1.3 Paths

Paths are one of the crucial components of the dynamic route planning system and form a connection from each node on the network to a place of safety. To improve the efficiency of computational resource use, all paths are generated prior to any evacuation event. This process is automated using a brute force method with certain heuristics are employed to reduce the required search space. These include the elimination of back tracking and entering rooms (nodes) that are defined as dead ends. Although it is clearly possible for occupants to follow such actions, it is most likely to be undesirable and therefore such paths are not considered. The number of paths that are saved from each node, in order of increasing length, is manually selected by the system user. This process of path generation is performed prior to any application of the system.

The following attributes about each path are saved to a data file:

- List of nodes on path – List of each node's identifier.
- Node breaks – Each entry refers to the total travel distance along a path where occupied node changes.
- Path length –Total distance from the centre of starting node to final safe node.

It is necessary to ensure that an adequately diverse path set is created. This is due to the number of available paths being reduced when hazard sensor data is considered during a system execution. For example from all nodes on a ground floor there should be at least one path saved from that node to each exit. Or if a node is on an upper floor of multi-floor building at least one path should be stored between that node and each stairwell leading to the lower floor, and then to each subsequent exit or further stairwell. This is demonstrated in Figure 2-4. From the initial location on the 1st floor there are 4 paths (represented with solid colour lines) that use stair 1 that are shorter than the shortest path possible using stair 2 (dotted line). It is necessary to save path details utilising both stairwells so if only a total of 3 paths were being saved from 1st floor nodes they would include the 2 shortest paths utilising stair 1 and a single path utilising stair 2 despite being longer than the next shortest paths through stair 1. It is obvious that the number of required paths from each node to maintain all stairwell/exit combinations will increase exponentially with the number of floors in the building. However, it would be sub optimal for there to be a theoretically safer path from one node but for it not to have been saved due to selecting a smaller number of paths to store. During a multiple solution execution the search space and number of paths to iterate between can be reduced by several heuristics, the details of which are explained later on in this chapter.

When the path file is read during a system execution, they are indexed by starting node as such:

Complete path list = [[x number of paths from node 1], [x number of paths from node 2] ...]

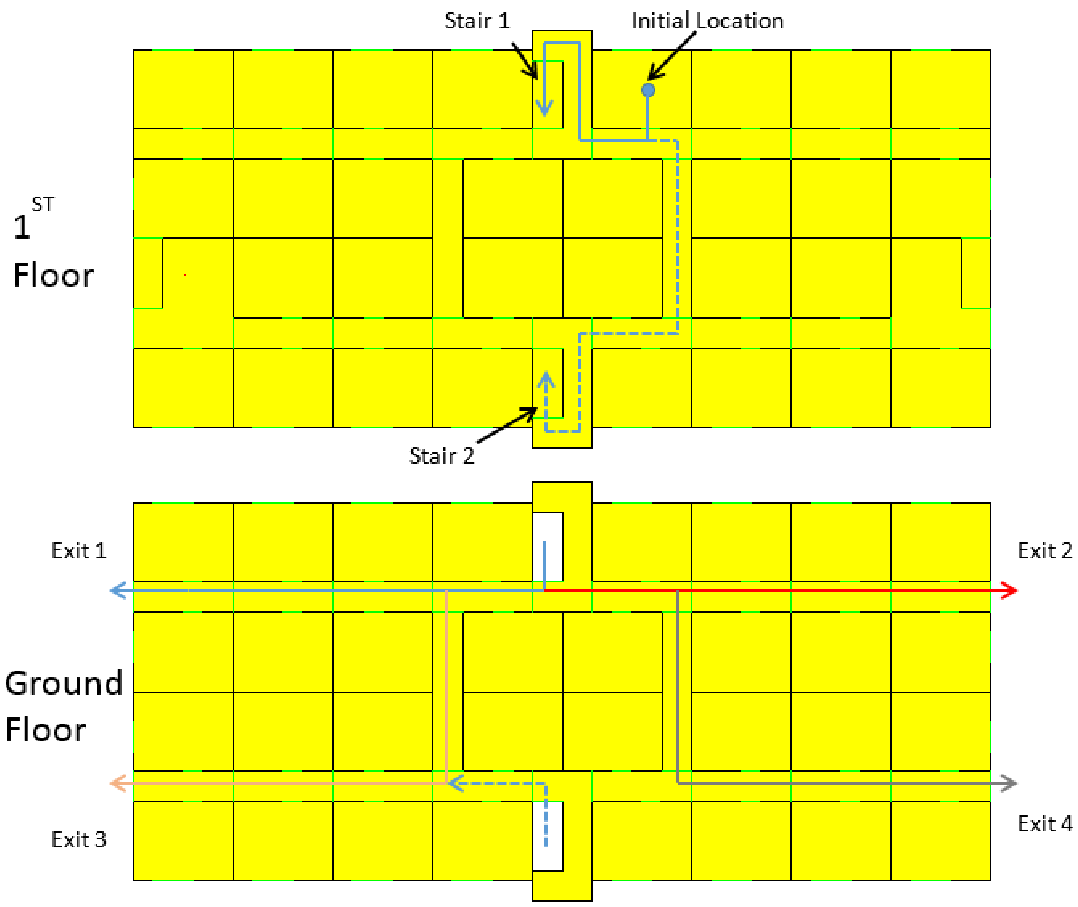


Figure 2-4 - Demonstration of path diversity over 2 floors.

2.2 System Input - Sensor and Alarm Data

The premise of the intelligent system is the ability to use sensor data to generate efficient evacuation plans. Throughout the project, the fire-risk model CRISP is used to replicate a real fire evacuation scenario and therefore all sensor data refers to files produced by this program. CRISP has been modified to produce simulated sensor data and details of which alarms have been activated, in the form of data files, every pre-determined number of time steps. This includes 3 different text files, one for each of the following; hazard details, occupant location and detector on/off state. The standard working functions of CRISP are not altered by this modification. These files can then be read and interpreted by the DRPS. The example simulations used to illustrate sensor and alarm data are shown in Figure 2-5 and Figure 2-6, with visual representations at initiation and after 120 seconds of simulation run time, respectively.

The limitations of the accuracy of this simulated sensor data is to represent a conservative view on current technology and the expense involved in setting up such a system. However, for the sake of the simulations carried out during this project, the various sensor outputs are assumed to be absolutely correct.

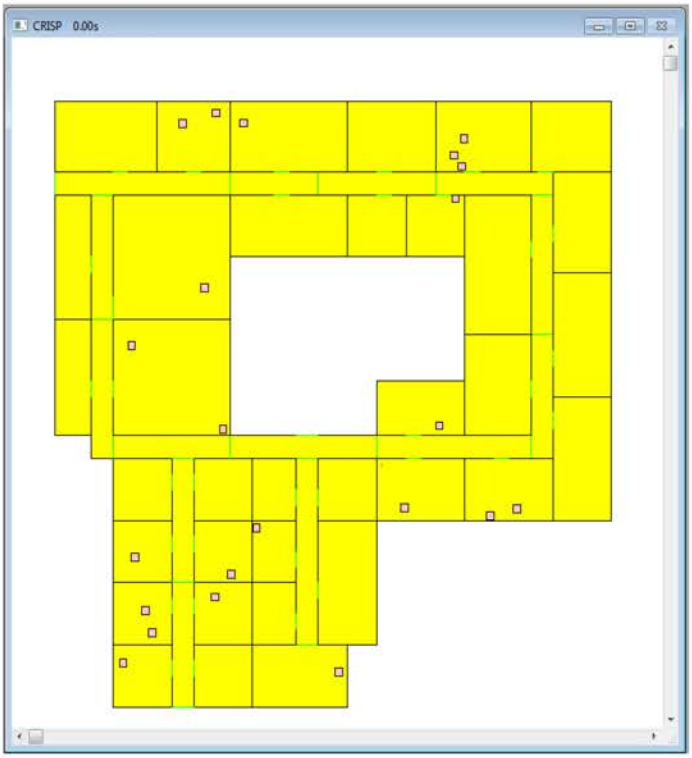


Figure 2-5 - Example CRISP simulation at initiation.

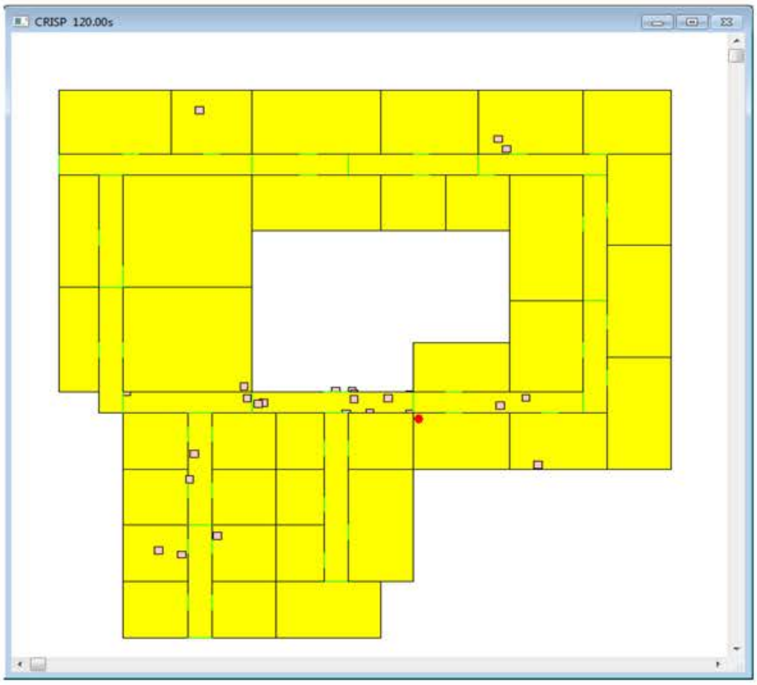


Figure 2-6 - Example CRISP simulation at 120 seconds

Occupant sensor data represents the location of each occupant accurate to the compartment which they inhabit. There is no knowledge of an occupants' precise location within a compartment although longer sections of hallway are split by open vents allowing a more accurate occupant location to be determined but have no effect on smoke flow. The left and right side of Figure 2-7 show the locations from the examples in Figure 2-5 and Figure 2-6 respectively. The first line represents the simulation time and each remaining entry represents the compartment/room number that each occupant inhabits. Each individual line of each occupant sensor data file refers to the same occupant, each time. This allows each individual's movement to be monitored and used to make more accurate movement predictions.

Fire/smoke hazard sensor data is represented by taking the upper (hot) layer temperature in the CRISP zone model for each compartment (room) defined in the building model. Figure 2-8 shows the hazard sensor output from CRISP for the examples shown in Figure 2-5 and Figure 2-6. The top line of the output represents the simulation time and each entry thereafter refers to the hot layer temperature of each compartment. This is representing the use of a temperature sensor, as per K-CRISP [1]

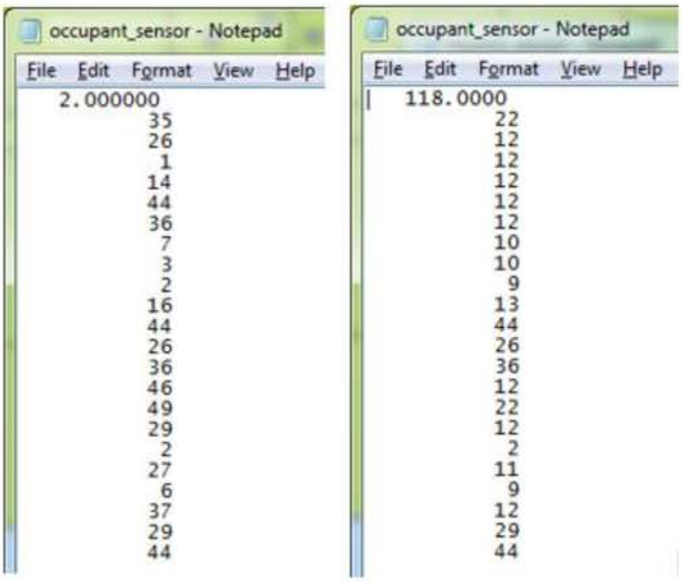
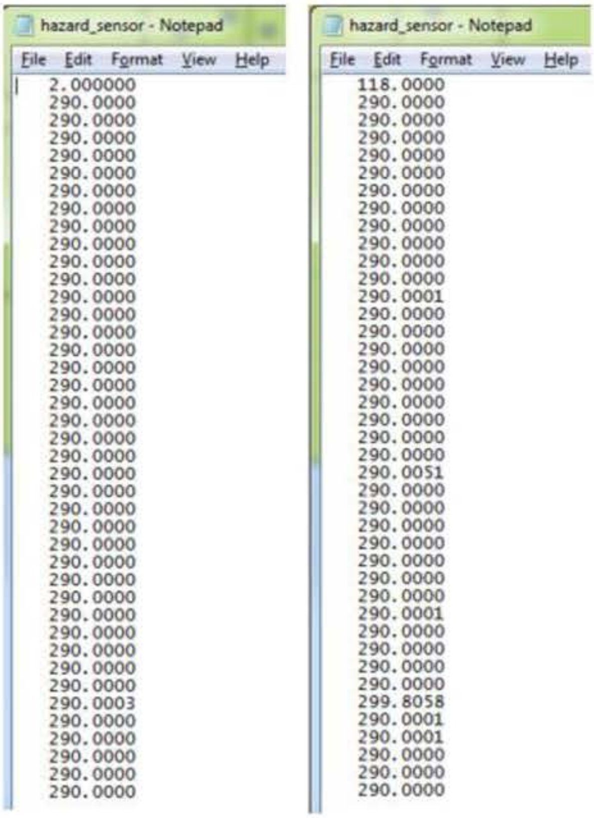


Figure 2-7 - Example CRISP occupant sensor output at initiation (left) and 118 seconds (right).

Alarm data is represented by an entry for each alarm showing the noise output which can easily be translated into an active/inactive. Where alarms are linked, it is necessary to determine which one was triggered first as it is assumed to be closest to the actual hazard location. All alarms are assumed to be working perfectly with no chance of failing to activate when required.



```
hazard_sensor - Notepad
File Edit Format View Help
2.000000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
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290.0000
290.0000
290.0000
290.0000
290.0000
290.0003
290.0000
290.0000
290.0000
290.0000
290.0000
```

```
hazard_sensor - Notepad
File Edit Format View Help
118.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0000
290.0001
290.0000
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290.0051
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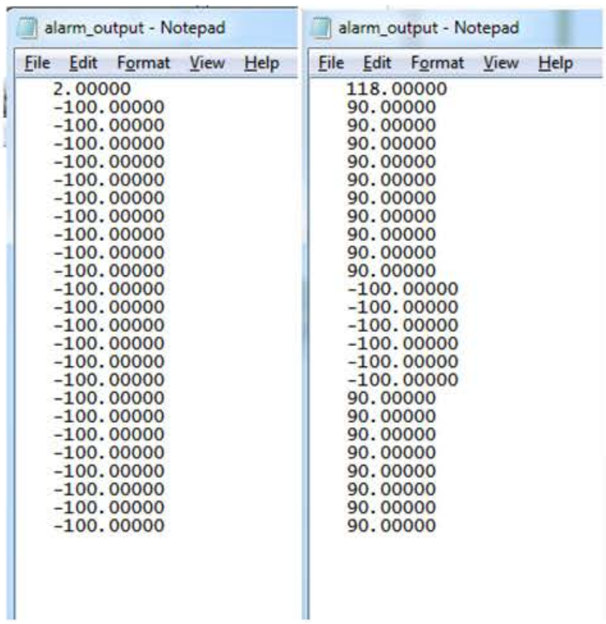
290.0000
290.0001
290.0000
290.0000
290.0000
290.0000
299.8058
290.0001
290.0001
290.0000
290.0000
290.0000
```

Figure 2-8 - Part example CRISP hazard sensor output at initiation (left) and 118 seconds (right).



```
alarm_output - Notepad
File Edit Format View Help
2.00000
-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
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-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
-100.00000
```

```
alarm_output - Notepad
File Edit Format View Help
118.00000
90.00000
90.00000
90.00000
90.00000
90.00000
90.00000
90.00000
90.00000
90.00000
90.00000
-100.00000
-100.00000
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90.00000
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90.00000
90.00000
```

Figure 2-9 - Part example CRISP alarm output at initiation (left) and 118 seconds (right). The numbers represent output volume with -100 showing that an alarm is inactive.

2.3 Dynamic Route Planning System Methodology

2.3.1 Sensor Data Interpretation

The first requirement within any execution of the DRPS is to interpret the sensor data in a manner that can be used to generate efficient evacuation plans. During a single or multiple system execution, the latest hazard sensor data is transformed into a hazard level between 1 and 5, in increasing level of severity, for each node. Where two or more network nodes are representing one CRISP compartment, the hazard level of both nodes is set to the level appropriate to the compartment. An example of this can be seen in Figure 2-2 where nodes 9 and 10 are both within the same CRISP compartment.

The temperature thresholds for each hazard level can readily be adjusted by the user. An example of how they could be set is:

[291, 310, 330, 380, 510] = node hazard level [1, 2, 3, 4, 5]

Each entry is in Kelvin with an ambient temperature of 290K. It may appear overly sensitive to use 1 degree above ambient as the threshold for a hazard but while CRISP is being used to simulate the real fire scenario, it is justified due to the absence of difficult to predict temperature fluctuations that would likely occur in a real life environment.

Alarm data is used to supplement the hazard sensor data. When comparing the overall safety between steered and un-steered evacuations it is necessary to conduct fair tests. This is ensured by re-setting all hazard levels to 0 when no alarm has been triggered, representing the system being inactive until the fire has been detected, even if the upper layer temperature in any compartment has increased beyond the threshold for hazard level 1. Justification for this is that the temperature is likely to have risen more than 1 degree within a compartment before an alarm is activated. If the alarm was outside the compartment of fire origin then this difference would be further exasperated. Any node which contains an alarm that has detected a hazard is given a minimum hazard level of 1 although if the temperature change is adequately high, it could be greater. It should be noted that DRPS node hazard levels and CRISP tenability levels are not directly connected. The DRPS has no direct knowledge of tenability levels of CRISP compartments and only takes temperature and detector on/off state data to determine the hazard level. It is likely that CRISP compartments with a lower tenability level will have either triggered an alarm/detector or have an above ambient hot layer temperature therefore giving the equivalent DRPS nodes a non-zero hazard level. However, it is also possible for compartments that have no change in tenability level to have been assigned a hazard rating due to the sensor data.

The occupant sensor data is interpreted to give a node location for each detected occupants' compartment. Once again there are can be two or more DRPS network nodes per equivalent CRISP compartment as in the example in Figure 2-2. If this is the case then the initial location is set to the centre of the node that is furthest from a place of safety which in this case is node 10 which is further from the nearest exit at node 59. If this is the first data being interpreted for this scenario then each occupant is also "created" within the DRPS and they have the following attributes:

- Identifier – Defining occupant number
- Name – A string which refers to the occupant number
- Location node – The current node that the occupant inhabits.
- Node step – The number of nodes that have been occupied by this occupant while on their path to safety.
- Speed – The walking speed at which the occupant will move while unhindered by other evacuees and not at any point in a building where speed would

normally be reduced e.g. stairs. This value was initially set at 1.4 m/s [41], which is on the fast side for average walking speed, across all demographics, but can be justified as an initial starting value as it can be adjusted if necessary when perpetual occupant movement monitoring (described later) is included. Conversely, it is on the conservative side when considering the graph shown in Figure 2-16.

- Nodes travelled – List of node identifiers through which the occupant has travelled (used for movement monitoring only and not during egress solution generation/evaluation).
- Recorded movement – List with entry of detected distance travelled for every time gap between senor data being received (used for movement monitoring only and not during egress solution evaluation).
- Total distance – Total distance travelled during solution evaluation.
- Safe – Boolean defining whether occupant has reached place of safety during solution evaluation.
- Path node speed factor – The multiplier being used to adjust the occupant movement speed for each remaining node on the path of the occupant, depending on the population density of each of these nodes.
- Priority - Used during multiple execution runs. A Boolean which determines whether an occupant's path is required to be prioritised due to their proximity to the detected fire origin. The situations in which an occupant is defined as priority is explained in the following section.
- Priority Path - If priority equals true, then this represents the equivalent path the occupant was instructed upon during the previous system execution - i.e. to maintain direction.

During operation, the system will repeatedly review the latest available sensor and alarm data until there is a detected hazard, in which case suitable path selection for solution generation and evaluation will begin based on that input data. If no hazard or alarm is detected then the system will pause until new sensor data is available. It is also necessary to check that the sensor data is complete which is ensured by checking that the length of the files is equal or greater than the longest previously interpreted. This is to prevent issues arising from one program attempting to read a file that has only been partly written.

During a single execution run, or during the first execution of a multiple execution run, the fire seat node is assumed to be that with the highest hazard level immediately after an alarm has been activated. This knowledge is the used to determine which occupants are of highest priority during the evacuation.

2.3.2 Path Selection for Solution Generation and Evaluation

It is likely that smoke will spread beyond the areas of detected hazard in the time it takes to move all occupants beyond these danger areas. For this reason it is deemed important to direct occupants far away from hazardous areas if possible. This is achieved by allocating a hazard value of 0.5 to all nodes, excluding those representing places of safety, that are adjacent to nodes with a hazard level of 1 or greater. An

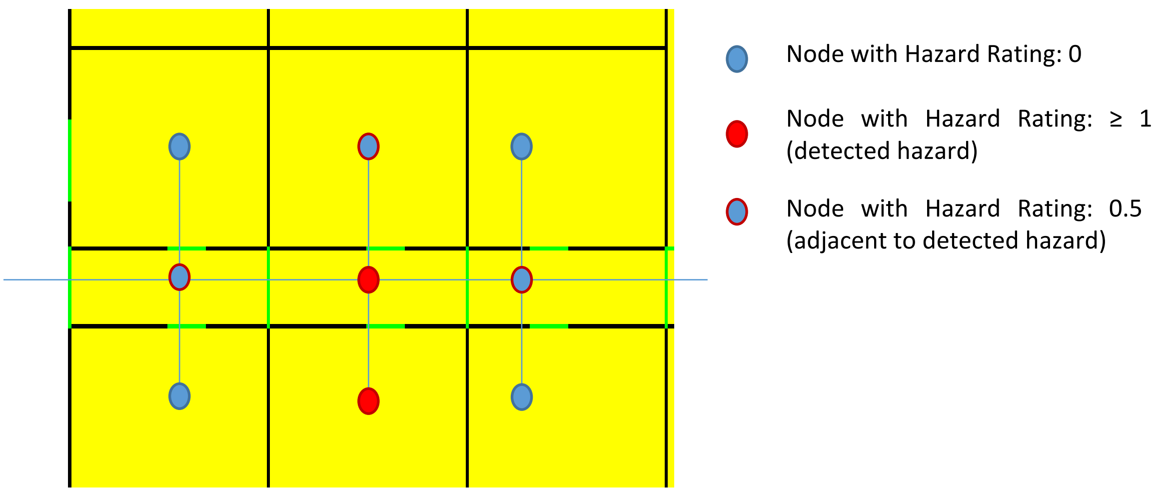


Figure 2-10 - Allocation of Additional Hazard Rating example demonstrating this is shown in Figure 2-10.

Due to the probable large number of possible paths available from each populated node, it is likely that some of these are affected by the detected hazard. For this reason a hazard cost value is determined for all paths from each node which has a detected occupant. This is calculated by the following equation:

$$P_{HC} = \sum_{i=1}^{P_N} \mathrm{N}_H \tag{2}$$

Where:

$P_{HC} = Hazard\ cost\ of\ path$

$P_N = Total\ number\ of\ nodes\ on\ path$

$\mathrm{N}_H = Hazard\ level\ of\ node$

For each populated node, the paths with the lowest or equal lowest hazard cost are saved in a new list.

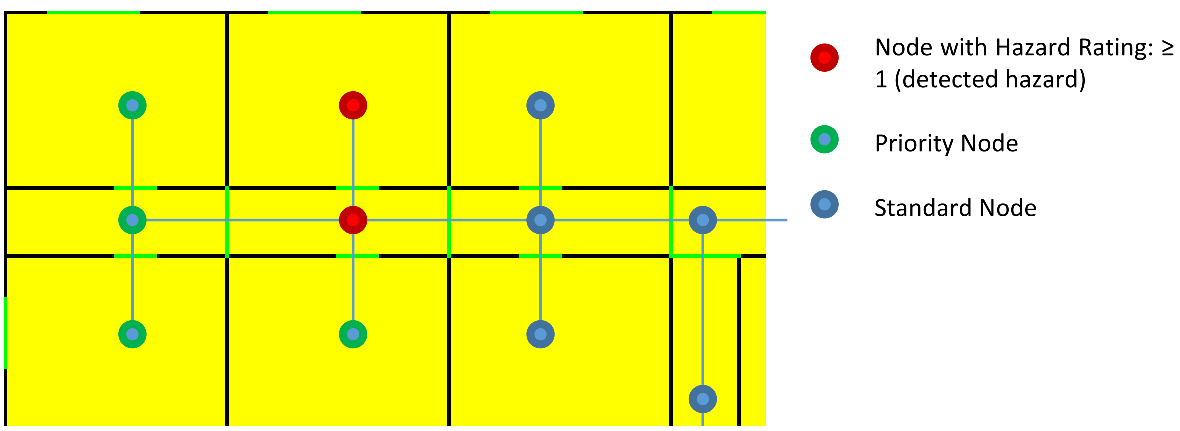


Figure 2-11 - Priority Node Explanation

Occupants inhabiting nodes from which all paths to safety involve travel through a node with a detected hazard (not additionally allocated hazard) are considered priority during solution generation. Note - green vents leading to the outside are windows and this diagram is representing a building's upper floor.

It is inevitable that there will be some populated nodes with no safe path available, an example of which is shown in Figure 2-11. During multiple execution system runs, in all executions other than the first, any populated nodes from which all paths use a node that is identified as a fire seat node (most likely a single node) have their habiting occupants considered priority. This results in their path which they were instructed upon during the previous system execution, is maintained during the current execution if it is still considered safest or equal safest compared to other paths from the node. The goal of this is to avoid a possible change of direction and subsequent increase in time spent in a dangerous location. This situation is most likely to occur when there is hazard symmetry between two possible paths (Figure 2-12). Occupant in populated node has two available paths of equal hazard cost (1.5 in this case). Once they have crossed onto the next node on their path (hazard level 1) their path choices are still between 2 of equal hazard, which is why the priority heuristics were implemented. Repeated changes in direction could result in unnecessary additional time spent in close proximity to the hazard.

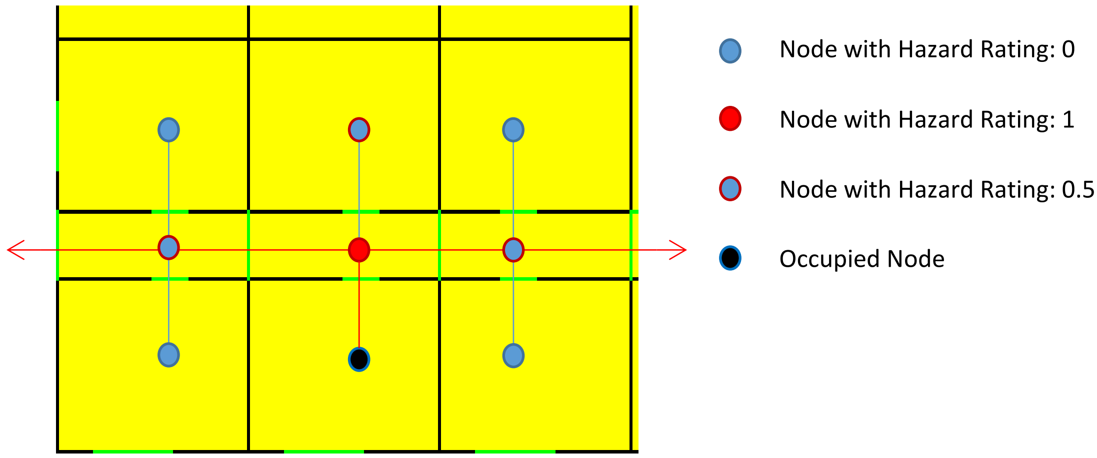


Figure 2-12 - Path Hazard Symmetry.

Some populated nodes are still likely to have a large number of safe available paths so it is imperative to further reduce the search space before solution generation and evaluation begins. If the building has more than one floor, then one method for achieving this is to use further heuristics to reduce the number of available paths for occupants on the ground floor (or the floor containing the majority of the exits to safety) is to direct them away from stairwells. An advantage of this is that when the occupants on upper floors reach the bottom of the stairwells there is a reduced chance of occupants who were originally on the lower floor impeding further movement. During a single system execution or for the first execution of multiple system execution occupants on the ground floor are instructed as such, the details of which are explained in Figure 2-13 and Figure 2-14. All of these assume that the shortest path chosen is available in terms of hazard cost. In Figure 2-13 the initial path for occupants on the ground floor (hazard permitting) is selected by determining which paths from each stairwell will pass through the occupied node (or adjacent corridor if node is a dead end like in this example). The shortest path (dotted line) from stair 1 which uses the occupied node uses the bottom right hand exit. The shortest path (solid line) from stair 2 which passes through the occupied node uses the bottom left hand exit. The latter of these will be selected as it is the shorter of the considered paths. This has the effect of minimising the influence of occupants at this node will have on movement from both stairwells. The next example shows that it may not always be appropriate to direct occupants down the shortest available path.

Figure 2-14 shows a hypothetical example where the occupant will not be directed on the shortest available path (to exit 1) but will be directed away from the stairwell towards exit 2 instead. It should be noted that these stairwell evasion rules only apply to the ground floor, as it would clearly be impractical to direct occupants on other floors away from stairwells.

In addition to this method of search space reducing, the total number of paths available from areas on other floors can be capped to a specified number. This occurs on all executions of multiple and single execution system runs although path diversity is still maintained (Figure 2-4) and any priority occupants and their defined paths are still assumed as such. All paths are then sorted in increasing order of length.

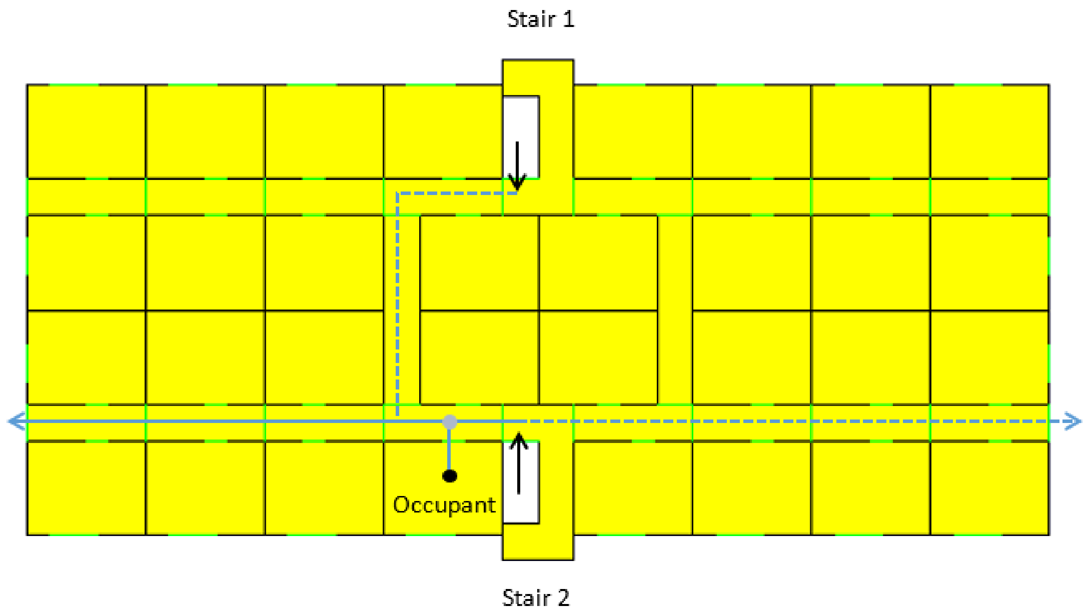


Figure 2-13 - Path Selection to Clear Stairwells (1).

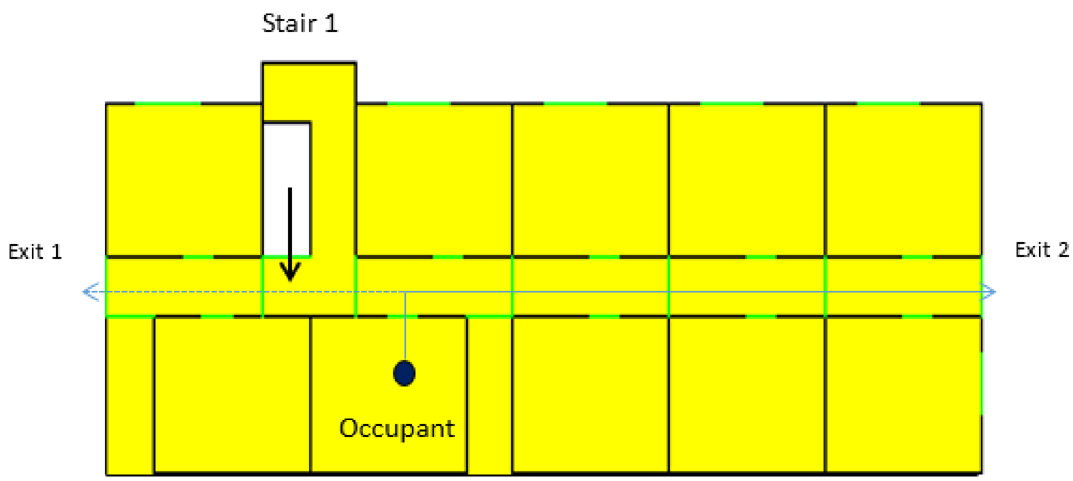


Figure 2-14 - Path Selection to Clear Stairwells (2).

2.3.3 Solution Generation and Evaluation

An egress solution represents a path allocated to each individual occupant from their original location node to a place of safety. They are represented by a list of path indices, each referring to a safe or equally safe path, for each occupant. For example if there were 5 occupants in the scenario a solution would be represented by what will be referred to as a “solution string” like this:

Egress solution string = [1, 0, 2, 4, 1]

A number 0 refers to the shortest, safest or equal safest path to safety from the first occupant’s original location node; a number 1 represents the second shortest, etc. If there are 5 stored paths from each node then these are selected between 0 and 4.

The solution evaluation predicts what will occur in terms of total evacuation time, the location of each occupant at each time interval and the total exposure to danger experienced across all occupants. This is while assuming all occupants follow their allocated paths precisely. The only interaction between occupants involves the effect of population density on movement speed.

The methodology of how the solutions are generated and evaluated, after the sensor data has been interpreted, is now described. Note that this is only using the latest available (instantaneous) sensor data and not making any predictions based on cumulative sensor data (perpetual occupant movement monitoring).

2.3.4 Solution String Generation

For each system execution (entire run of the system from sensor data input to route instruction output) and each defined number of solutions to be generated and evaluated within each system execution: a solution strings is created. Each populated node has been left with a set of possible available paths, each of which is defined by an index within a set. For example $P_{node} = \{0,1,2\}$ which shows that three paths are currently available from this node. The conditions by which the path for each occupant is selected for each execution and solution are defined in the following table.

Conservation of path direction is necessary to prevent occupants being needlessly changed direction when their choice of paths appears inconsequential to the overall evacuation safety. This can occur due to the symmetrical nature of some of the building layouts used throughout this project. Constant changes in direction can lead to corridors getting blocked which can have the subsequent effect of other occupants being unable to leave an area of danger. These reasons are only those that apply to the simulated environments. Instructing real people to regularly change direction would likely fail to improve overall evacuation safety and efficiency.

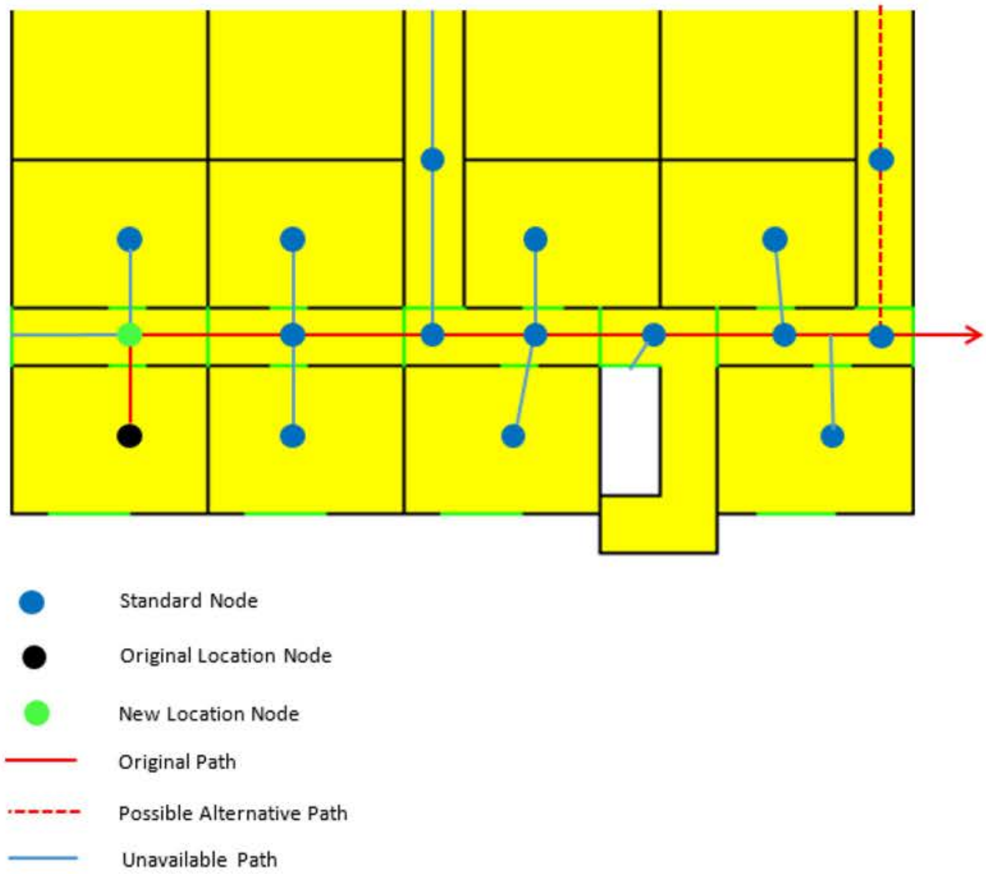


Figure 2-15 - Conservation of Path Direction.

The method for achieving this is by comparing the occupant's current node location to the path they were instructed upon during the previous system execution and determining how many steps along the path they have taken since. Then, during the current system execution only paths which share the following specified number of nodes are considered available. An example of such a situation is shown in Figure 2-15. This example shows what paths are considered available to an occupant who has moved nodes between subsequent system executions. The number of nodes which a new path must share with the original path, beyond the new location node, is set to 4. If this was changed to 2 then the first (leftmost) path leading upwards in the diagram would also be considered available.

Case	**Path Index Selection Criteria**
E = 1 and S = 1	0 (shortest available path, UFP)
E = 1 and S > 1	Randomly selected index from path set.
E > 1 and S = 1	Index which represents the equivalent path that the occupant was instructed upon during previous system execution (E - 1) where available, otherwise a randomly selected index from the path set, while adhering to conservation of path direction (explained below).
E > 1 and S = 2	0 (shortest available path UFP), where adhering to conservation of path direction maintenance and priority occupants.
E > 1 and S > 2	Randomly selected index from path set while adhering to conservation of path direction and priority occupants.

Table 2-1 - Path Index Selection Criteria

Where:

E = System execution number.

S = Solution number within current system execution.

2.3.5 Solution Evaluation

It is now necessary to determine the potential of each solution (path set) is, by calculating the overall exposure to danger experienced across all occupants at all time steps. Each occupant is considered to start the evacuation at the centre point of each of their original node location. It should be noted that pre-evacuation time is not considered during solution evaluation, or by the DRPS as a whole, which assumes occupants start evacuation along the chosen path immediately. This can be justified by the dynamic aspects of the DRPS, in that if occupants commence their evacuating with different time delays, the system can react by updating route instructions accordingly. Additionally, many system executions will occur after occupants have started evacuating, where pre-evacuation time would not be applicable.

Solution evaluation works by iterating each occupant's movement individually for each time step until all occupants have reached a safe node. In essence, solution evaluation is making a prediction of what will happen if occupants follow this particular set of paths. The method for determining each occupant's movement is described by the following steps:

For each occupant within each time step:

1. Determine if occupant is safe or not. If not then:
2. Determine how the current population density of each node on the occupant's path will affect their movement speed when they reach that node.
   2.1. The apparently population density is calculated as follows

$$\rho_A = \frac{number\ of\ occupants - 1}{working\ area} \tag{3}$$

   Note: The "-1" is used to ensure that an occupant that is the only inhabitant of a node does not cause a reduction in speed, which could otherwise occur if the working area is sufficiently low.

2.2. A speed adjustment factor (AF) is then determined depending on ρ_A (Table 2-2)

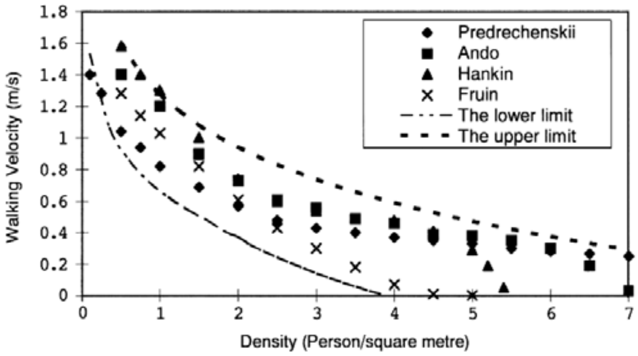


Figure 2-16 - How crowd density affects walking velocity. Graph taken from previous work [42]

ρ_ARange (occupants/m^2)	**Speed Adjustment Factor (AF)**
$0 < \rho_A \leq 0.4$	1
$0.4 < \rho_A \leq 0.8$	0.82
$0.8 < \rho_A \leq 1.2$	0.68
$1.2 < \rho_A \leq 1.8$	0.54
$1.8 < \rho_A \leq 2.5$	0.43
$2.5 < \rho_A \leq 3.5$	0.37
$3.5 < \rho_A \leq 5.0$	0.29
$5.0 < \rho_A \leq 7.0$	0.21
$7.0 < \rho_A < \infty$	0.14

Table 2-2 - Estimated required density speed adjustment factors based on graph in Figure 2-16

If the node is defined as a stairwell then the adjustment speed factor is defined by:

$$AF_{STAIR} = \frac{AF}{2} \tag{4}$$

This is a simple estimated modifier for movement speed on stairwells and once again, can be justified as an acceptable initial value due to the use of perpetual occupant movement monitoring (section 2.5) to change these adjustment factors where appropriate. For this reason, a more sophisticated set of rules for determining movement speed on stairs was not considered necessary and the actual impact stairwells have on movement speeds in the CRISP model, was not included.

3. Determine how far along the path the occupant will move this time step.

$$T_b = V_b t \tag{5}$$

Where:

T_b = Basic travel distance

V_b = Basic movement speed

t = length of time step (usually 1 second)

Remaining travel (T_r) =

$$T_r = T_b \tag{6}$$

3.1. Loop while $T_r > 0$

3.1.1. Calculate distance still to travel until reaching the next node (N_r).

3.1.2. Calculate the amount of travel distance that remains after adjusting for the current node's population density using the following equation.

$$T_{r,a} = \begin{cases} N_r + T_r - \dfrac{N_r}{AF_n}, & T_r AF_n > N_r \\ T_r AF_n, & T_r AF_n \leq N_r \end{cases} \tag{7}$$

Where:

$T_{r,a}$ = Remaining travel distance adjusted after current node population density has been considered.

N_r = Remaining distance to travel before next node on path is reached.

T_r = Remaining travel distance this time step for this occupant.

AF_n = Speed adjustment factor for node n.

3.1.3. If $T_{r,a} > N_r$ and the occupant is not already on the last node then:

3.1.3.1. Move occupant to the next node and adjust travel remaining as follows:

3.1.3.2. $T_r = T_r - T_{r,a}$

3.1.3.3. Return to step 3.1.

3.1.4.Otherwise: $N_r = N_r - T_{r,a}$

4. Check if occupant has reached safety.
5. After iteration of all occupants has been completed for the current time step it is necessary to calculate the hazard exposure experienced during this time step.

$$S_{HC,t} = \sum_{i=1}^{O_T} N_H \tag{8}$$

Where:

$S_{HC,t} = Hazard\ cost\ of\ time\ step$

$O_T = Total\ number\ of\ occupants$

$N_H = Hazard\ level\ of\ node$

6. The solution is checked at the end of each time stage to see if the cumulative solution hazard has reached the threshold level for the solution. This threshold is defined as the minimum hazard cost of all solutions yet evaluated. A solution will be terminated if it reaches or surpasses the threshold level, depending on the

solution and execution number. How the cut off varies between executions and solutions is described as such:

$$H_{cut\,off} = \begin{cases} \infty, & E, S = 1 \\ H_{threshold} + 1, & E = 1, S = 2 \\ H_{threshold}, & E = 1, S > 2 \\ H_{threshold} + 1, & E > 1, S \leq 2 \\ H_{threshold}, & E > 1, S > 2 \end{cases} \tag{9}$$

Where:

$H_{cut\,off} = Hazard\ cutoff\ limit$

$H_{threshold} = Hazard\ cost\ of\ previous\ safest\ discovered\ solution$

$E = Execution\ Number$

$S = Solution\ Number$

7. If the first solution of a system execution is found to have a hazard value of 0, then the solution cut off threshold is switched to instead depend on the number of time steps required to complete evacuation. This works in the same way as hazard threshold levels with a solution being terminated once it has surpassed the threshold level. The reason for premature solution termination is that if a solution is already deemed to be more hazardous than one already evaluated, then it is a waste of computational time to evaluate it to conclusion and it makes more sense to move onto the next solution as quickly as possible.

$$t_{cut\,off} = \begin{cases} \infty, & E, S = 1 \\ t_{threshold} + 1, & E = 1, S = 2 \\ t_{threshold}, & E = 1, S > 2 \\ t_{threshold} + 1, & E > 1, S \leq 2 \\ t_{threshold}, & E > 1, S > 2 \end{cases} \tag{10}$$

Where:

$$t_{cut\ off} = Number\ of\ time\ steps\ reached\ before\ solution\ terminated$$

$$t_{threshold} = Time\ of\ fastest\ \ discovered\ solution$$

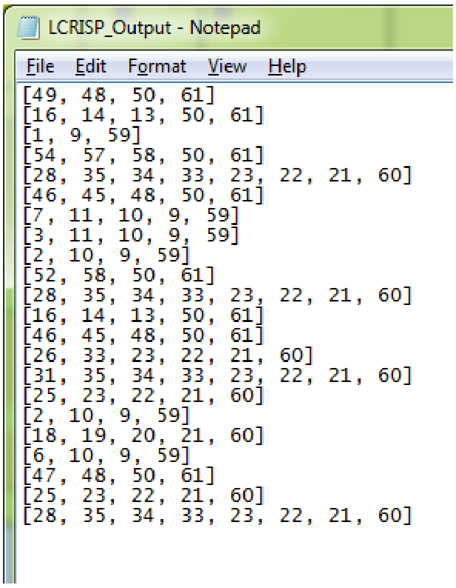
$$E = Execution\ Number$$

$$S = Solution\ Number$$

2.4 System Output

After all solutions for the current system execution have been evaluated, the safest or fastest equal safest path set is selected. During a multiple system execution, the process is then repeated with the next available sensor data and the first evaluated solution being the equivalent of the chosen solution of the previous execution.

An example file for the same example scenario can be seen in Figure 2-17. Each line represents a path for each occupant, in the same order in which they were originally detected. Each entry on each line represents a DRPS network node with the final node being a place of safety. When steering CRISP simulations these nodes need to be converted to the appropriate CRISP room number.

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[2, 10, 9, 59]
[18, 19, 20, 21, 60]
[6, 10, 9, 59]
[47, 48, 50, 61]
[25, 23, 22, 21, 60]
[28, 35, 34, 33, 23, 22, 21, 60]
```

Figure 2-17 - Example System Output

2.4.1 CRISP Steering Modifications

CRISP has been modified to allow for the DRPS created data file to automatically steer occupants along the chosen paths. Each line in the data file contains a list of numbers for each occupant that represent the CRISP room numbers that comprise the path which each occupant is intended to follow. During steered evacuations, the occupants are influenced by changing their CRISP action to “escape” and their target room to the next room on the intended path. If an occupant appears to have deviated from a path (i.e. not occupying any of the rooms that comprise the instructed path), which can occur due to complex building room layouts being simplified for the DRPS node network, they are instructed to the exit or stairwell entrance that matches their instructed path and current floor. An occupant with the action “escape” will commence evacuation along their set path immediately and will not undertake any other action (warning others, fighting the fire or waiting to evacuate etc.).

To represent the likelihood of occupants in a real life evacuation scenario ignoring or failing to understand such instructions, a range of obedience levels were tested. At the beginning of a CRISP simulation, a pre-determined percentage of the total occupancy will be considered disobedient. Precisely which occupants are declared as disobedient is defined at random at the beginning of the simulation. Those initially defined as such will remain so for the duration of the simulation. A disobedient occupant is simply alerted to fact an evacuation is occurring (i.e. they are not asleep, nor oblivious to the alarm), but does not have their action changed to “escape” and is not instructed along a path (given a target room which they should aim for as they escape). They are left to follow the original human behavioural rules defined within CRISP and are allowed to perform any action. These occupants act as if they were in an un-steered simulation.

There were also tests carried out where the occupants had their action changed to “escape” but were not instructed on which specific route to follow. This would result in occupants commencing evacuation immediately after the hazard was detected, but their route choice would be determined by the standard CRISP route planning rules, rather than a DRPS selected path. A result of this steering method was that occupants would usually choose the shortest route. The purpose of this steering method was to compare the FED results of simulations with evacuation routes that had been selected by the DRPS against those that were selected by the human behavioural models in CRISP, while maintaining the same negligible pre-movement time. This is because completely un-influenced (un-steered) simulations will include some pre-movement time compared to the steered occupants. Occupants defined as disobedient, during steered simulations can also include pre-movement time.

2.5 Perpetual Occupant Movement Monitoring

By continually monitoring the location, and thus movement of occupants during an evacuation scenario, either real or for training purposes, it is possible to infer specific movement patterns throughout a building. Areas where occupants are moving slower than expected, due to, for example, previously unknown pieces of furniture, can be identified. Such information, when derived from trial evacuations, could be implemented during subsequent, genuine emergencies to improve the accuracy of predicted movement patterns within solution evaluation and thus, overall safety.

If the maximum speed detected in a node is lower than standard walking speed, then it can be assumed necessary to reduce the free movement (when AF = 1) for this node during subsequent solution evaluations. In addition the average occupant speed, at all detected population densities, in certain areas could be different to what is expected in which case the assumed working area for the node could be adjusted accordingly. Working area can be adjusted to both standard walking speeds and detected walking speeds.

2.5.1 Post Evacuation Analysis

Post evacuation analysis would allow predictions of future movement speeds and population density to movement speed ratios to be made before any future evacuation event. If it is possible to gather movement data from a number of trial evacuations, this has the potential advantage of providing more accurate predictions due to the greater volume of data than what could be accrued during a live fire evacuation. As the parameters: unhindered movement speed and working area of each node; which are crucial to the output of the DRPS, were initially estimated, post evacuation analysis will change these values if appropriate.

A number of CRISP simulations can be run with the DRPS monitoring the sensor data, but not influencing the evacuation. This was done using CRISP in trial mode, so no hazard was present and pre-movement times were zero. Justification for using trials is that this is the most practical method by which this information would be obtained for a real world building. The more trial simulations that are used to gain this data, the more useful the results are. Occupant sensor data allows, for each CRISP simulation, the location of each occupant at each time step to be determined. In turn, this also allows for the movement speed for each occupant at each node, at each time step to be determined. This, combined with knowledge of the number of occupants at each node at each time step, makes it possible to infer what impact population levels have on movement speed, at each node. For example; if it appears that movement speed has been negatively impacted to a greater degree by the number of the occupants than expected, then the original value for the working area for that node was too high. If the opposite is true then the working area was too low. Free movement speed can also be taken from this data and the recommended adjustments for this and working area, for each node, are then stored in data files that can be accessed by the DRPS at a later time (similar as for store path data). The methodology for determining the working area and free movement speed for each node through use of occupant location sensor data, after an evacuation has taken place is now described.

After an evacuation, all occupant location sensor data accrued throughout can be used to determine which path each occupant used to exit the building and the length of time spent on each node. It will often be necessary to fill in node gaps in the sensor data where an occupant has moved by more than one node step along a path, during the time between two data files being received. If a CRISP room is represented by more than one possible node, the sensor will automatically assume that the occupant is at the furthest node from safety. However, this may not be on the actual path travelled so the node location determined from the sensor data will have to be adjusted appropriately (Figure 2-18).

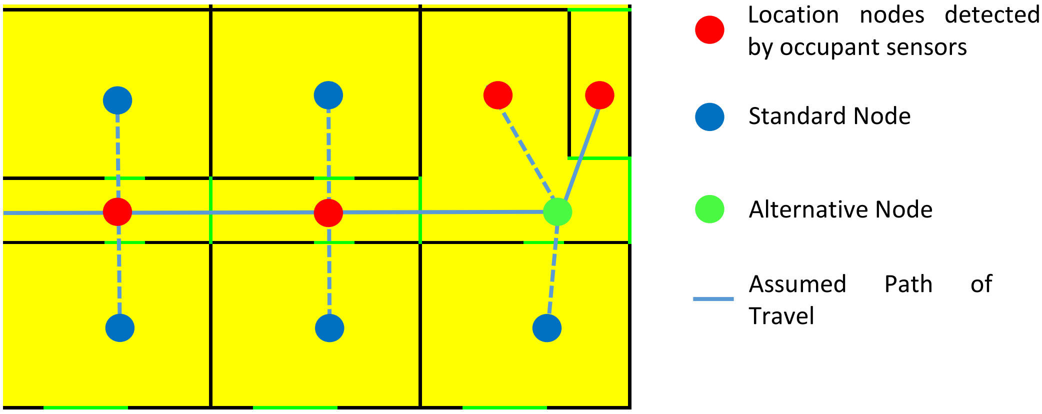

Figure 2-18 - Alternative Node Selection.

The red nodes represent the occupant's path were the sensor data interpreted literally. However as this does not represent any saved path it is unlikely that they travelled along this exact path during evacuation. Occupant movement predictions are then based on them being assumed to have travelled through the alternative node (green).

It is then necessary to calculate the time each occupant spent at each node on their path, including those of which were not directly detected, and thus each individual's speed through each node. This is described by Figure 2-19 and the subsequent equation. The time calculated to have been spent on any node that was not directly detected by sensors is limited to the time gap between these sensor readings. By calculating where each occupant was at every discrete time step it is also possible to determine the population of each node at each time step.

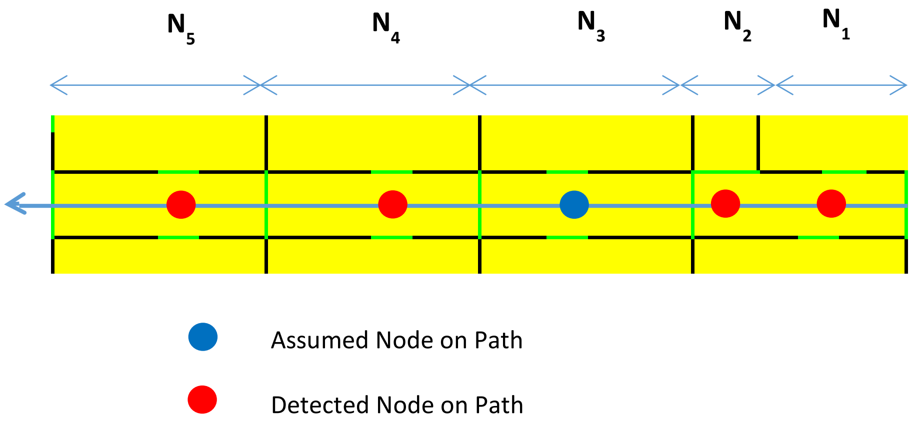

Figure 2-19 - Calculating time spent on nodes not detected directly.

$$T_3 = \frac{N_3}{N_1 + N_2 + N_3}(T_5 - T_2) \tag{11}$$

Where:

$T_x = Time\ elapsed\ upon\ occupant\ deemed\ to\ be\ entering\ node\ x.$

$N_x = Total\ travel\ distance\ across\ node\ x$

The combination of the time spent at each node, and the node length, allows the average and movement speed of all occupants at each node at each time step to be calculated as well as the maximum detected movement speed at each node across the entire evacuation. By comparing the average speed at each node at each time step with standard speeds the required speed adjustment factor is determined. The required apparent population density $(\boldsymbol{\rho_R})$ to achieve the measured speed reduction is calculated from the following table, which is a reversed version of Table 2-2 [42] where this time the speed adjustment factor is known.

Required Speed Adjustment Factor Range (AF_R)	$\boldsymbol{\rho_R}$ **(occupants/m^2)**
$0 < \mathbf{AF_R} \leq 0.14$	7.0
$0.14 < \mathbf{AF_R} \leq 0.21$	6.0
$0.21 < \mathbf{AF_R} \leq 0.29$	4.25
$0.29 < \mathbf{AF_R} \leq 0.37$	3.0
$0.37 < \mathbf{AF_R} \leq 0.43$	2.15
$0.43 < \mathbf{AF_R} \leq 0.54$	1.5
$0.54 < \mathbf{AF_R} \leq 0.68$	1.0
$0.68 < \mathbf{AF_R} \leq 0.82$	0.6
$0.82 < \mathbf{AF_R} \leq 1.0$	0.4
$1.0 < \mathbf{AF_R} < \infty$	0.3

Table 2-3 - Required speed adjustment factor and resulting apparent population density

The adjusted working area is then calculated as follows:

$$adjusted\ working\ area = \frac{number\ of\ occupants}{\rho_R} \tag{12}$$

The previous few steps can be repeated to acquire a different estimate for the adjusted working area which uses the maximum detected speed at a node across all time steps, replacing the standard movement speed.

After the evacuation and monitoring are complete the following details about each node are saved to a data file:

- Maximum detected movement speed across all time steps.
- Adjusted working area based on average detected speed compared to standard free movement speed across all time steps.
- Adjusted working area based on average detected speed compared to maximum detected speed across all time steps.

This cumulative sensor data can then be used during subsequent solution evaluation with the idea that predictions about how occupants will move throughout the building will be more realistic. The aim of this is to determine more accurately the hazard cost of a path set, possibly resulting in a different, safer solution being selected.

2.6 System Application Method

Throughout the project, CRISP was used to represent a range of real fire scenarios in which the DRPS would influence occupants' choice of egress route using a range of steering methods. For each simulation, CRISP would produce a range of output data, including FED values and evacuation time. The effectiveness of each DRPS steering method was then compared, both with each other and with un-steered evacuations. Three different building scenarios were tested and the results for each of these are presented in Chapters 3 to 5. The general method for these tests is now described.

In terms of the actions required by the user, the tests come under two distinct categories: steered and un-steered. During steered tests, CRISP is run in approximately real time, to provide as realistic a scenario as possible. This option was already within the CRISP model and works by pausing the simulation, every time step, after the model has finished its tasks, until the real world time that has elapsed equals simulated time. For example, if 1 second is being used as the time step, and all the actions within the CRISP code for a single time step take 0.2 seconds to run, then the program will pause for 0.8 seconds to allow real world time to catch up. When the scenario is sufficiently complex (as in Chapter 4 and 5), the generation of sensor data files would cause CRISP to run slightly slower (approx. 20%) than real time. Throughout the remainder of the thesis, when the system is described as operating in "near real-time", this is what is being referred to.

The DRPS requires the number of executions and number of solutions per execution to be defined by the user, as well as for the path file to be in place prior to any test. To commence a steered test, CRISP and the DRPS are started running simultaneously, with no further action required by the user. Beyond starting, the coupled system is fully automated. Specific details of each test type are described separately for each scenario in chapters 3 to 5, but the basic user requirements are mentioned here. Un-steered tests do not require CRISP to be run in real time and therefore the results from these can be obtained quickly. The DRPS is not used for these tests at all.

For steering methods where route instructions are continually re-visited (dynamic), the number of system executions is set to an arbitrarily high number so that the system will run for the duration of the CRISP simulation. For non-dynamic (static) tests, the number of executions would be set to 1. Tests using multiple solutions (MSR) would use a number appropriate the scenario complexity. More complex scenarios would require fewer solutions to be evaluated to maintain the same run time compared to a scenario of lower complexity. As it is necessary, to meet the aims of the project, to ensure the DRPS produces route instructions in good time, a number of solutions that allows completion of a system execution within a few seconds, was chosen. The specific number of solutions used for each scenario is detailed in the appropriate chapter. Tests where only the shortest, safest or equal safest paths are considered (UFP) require the number of solutions to be set to 1.

CRISP is not run in Monte-Carlo mode for the testing in this thesis, as it is necessary to compare FED results for different steering methods using identical scenarios. If the same seed number is used to initiate a CRISP simulation, with the same set of input files, then the initial occupant distribution and hazard location will also be the same, which allows a fair test between different steering methods. A number of different seeds, each one being used with all steering methods, can then be used to test the system across a range of different initial set ups. This is to reduce the likelihood of overall trends being affected by exact specifics of the initial distribution of occupant location. Each seed is referred to as an initial condition set throughout the remainder of the thesis.

The system can also be run in movement monitoring mode, to gather the required sensor data for perpetual occupant movement monitoring. CRISP is run in real time, trial evacuation, mode for this and the DRPS gathers all the occupant sensor data until the end of the evacuation, after which the data is used to determine the detected speed and working area for each node.

2.7 System Development

The majority of the DRPS framework was developed before any of the results presented in this thesis were obtained. To ensure that the DRPS was producing verified outputs, step by step system executions were carried out using a very basic building layout with a small number of occupants. It was necessary for the scenario to be simple enough to feasibly allow hand calculations to be made for each occupant's movement, for each time step, albeit one where hazard cost and density affects can still be tested. DRPS output values for the exact distance moved and hazard cost for each occupant, for each time step, were compared with these hand calculations, which subsequently allowed any errors in the model to be identified and corrected.

A short evaluation was carried out to determine the initial values used for crowd density effects on movement speed (section 2.3.5). Three different sets of speed adjustment factors (AF) values were taken from the graph in Figure 2-16 to represent different levels of crowd density impact. The number of time steps, that the DRPS would suggests is required for an evacuation, was compared to actual evacuations in CRISP, with occupants in CRISP following the DRPS suggested path exactly. The building layout in chapter 3 was used for this evaluation. A set of AF values from the middle of the graph was found to be the most accurate at replicating CRISP evacuation times, and it was these that were used throughout the project (Table 2-2).

From an early stage in the project, it was clear that minimising the run time of the DRPS was crucial. Premature solution termination (section 2.3.5) was introduced when initially testing the system, as it was likely that some generated solutions would quickly be evaluated as less safe than previously discovered solutions. Evaluating such solutions to conclusion would be a waste of time as they would never be selected. This addition successfully reduced run time by approximately 50% for the building layout in chapter 3, after which the system was never run without.

Several of the important features and heuristics described in this chapter were introduced during development of the scenarios for each case study. These are now listed in the order they were added to the DRPS. Details of how each building layout was chosen are described in the appropriate chapter for that scenario. Additional hazard allocation (section 2.3.2) was introduced to prevent paths that use nodes adjacent to a detected hazard, being given equal safety status to those which are at the far side of the building. The requirement for this became obvious after initial testing of the coupled system

Giving certain occupants priority status (section 2.3.2) was introduced during development of the building layout in chapter 3, to stop occupants who had to pass through the fire compartment, having their path instructions changed while they were still in the fire compartment. Before this was introduced, an instructed occupant could walk back and forth across the fire seat multiple times. It should be noted that the fire used here was small and benign compared to those used in other scenarios. This rule was developed before the later "conservation of path direction" heuristic (section 2.3.4), which in turn was more widely applicable but less restrictive, which was added after the results from chapter 3 were obtained. Occupants who were in a part of the building where their choice of path had no impact on the overall result of the solution evaluation (far from the hazard) would constantly have their instructed paths changed. This resulted in increased evacuation times with occupants repeatedly travelling backwards and forwards along corridors.

Due to the increasing complexity between the scenarios in chapter 3 and 4, as well as considerations from the results of the former, universal fastest path (UFP) steering was introduced. The search space increase due to the greater number of rooms and occupants in chapter 4 has significantly increased the time requirements for solution evaluation. As UFP steering only considers one solution per system execution, path instructions can be produced near instantaneously. Comparing UFP with MSR results would then aid in determining the benefits of differing levels of DRPS sophistication.

Perpetual occupant movement monitoring (section 2.5) is a major feature that was added to the system after the results in chapter 3 had been obtained, due to it being an idea developed at this stage. As the scenario in chapter 3 wasn't deemed sufficiently challenging, further tests using that building layout with this additional functionality were not carried out.

Ensuring that a diverse range of paths (section 2.1.3) was being saved for system application was determined necessary when testing the first multi floor building layout (chapter 4). Without this, if saving, for example, details for 4 paths from each node, only one stairwell would likely be considered for use as these could comprise the shortest 4 paths. This could clearly result in the safest possible paths not being available for solution generation, which would not lead to an acceptable outcome. Although for the scenario in chapter 4, the problem could be avoided simply by saving a greater number of total paths, the issue would return when the system would be applied to a larger building.

Stairwell evasion (section 2.3.2) was also introduced while developing the scenario in chapter 4 as substantial queues were occurring on, and leading to stairwells, due to occupants on the ground floor being directed past the exit of stairwells. The effect of this was to significantly reduce the size of these queues.

In general, there are several aspects of the DRPS that could have had their mechanisms copied from the CRISP model. Some of these include using CRISP room tenability levels instead of hazard levels derived from temperature sensors/detectors, how occupant density affects movement speed and occupant movement speeds on stairs. However, it was decided against at an early stage in the project to do so, as this would infringe on the realism of using CRISP to represent real fire scenarios. This could allow DRPS solution evaluation to be unrealistically accurate, compared to if such a system were to be employed in real world environments. For this reason, the implications of using direct CRISP knowledge in this way this was never investigated.

3 Single Floor Building Scenario

The overall goal of the project is to demonstrate the potential of an intelligent egress system to improve evacuation safety across a range of scenarios and building layouts. This chapter represents the first stage in this process by demonstrating the concept of occupant steering with the proposed dynamic route planning system being applied to a simple single floor building, with a relatively small number of occupants. As perpetual occupant movement monitoring was not included in the DRPS at this stage, there are no results utilising adjusted speed or working area in this chapter.

3.1 Scenario Description

The building used in this chapter consists of 32 rooms arranged with 2 horizontally and vertically aligned corridors and is shown in Figure 3-1. There are four exits with one at the end of each corridor, so adjacent to CRISP compartment 35, 42, 45 and 52. Each room is 5m x 4m in dimension with doors leading to the corridors being 0.9m wide. The corridors are 1.5m wide and the intersections of these are completely open. There were a total of 40 detectors deployed throughout the building: one in each of the rooms (compartment 1 - 32) and then additionally placed in compartment 36, 41, 43, 44, 46 and 5. This building layout was chosen as it was used in early development of the DRPS, where it was originally designed due to ease of implementation within CRISP while being able to contain a relatively high number of occupants. It was not intended to represent a realistic building but is adequate for early demonstration of the system.

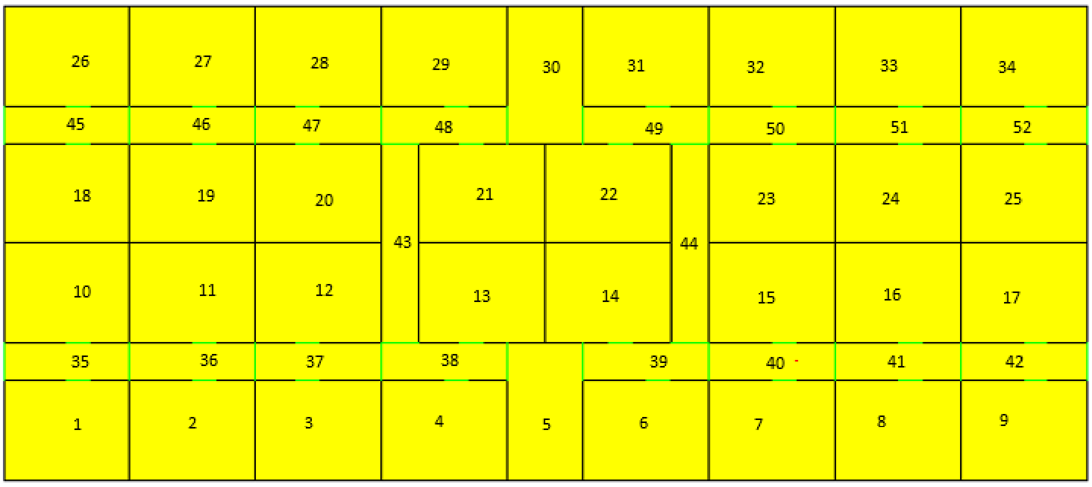

Figure 3-1 - Building Layout with CRISP room numbers (green lines represent vents that form the barrier between CRISP rooms - doors or open archways).

3.2 Test Method

For each steered test type a total of 60 simulations were executed and for each non-steered test types, there were 100 simulations. This is due to the speed at which results from un-steered simulations can be obtained. These comprised 20 different initial condition sets with steered test types being repeated three 3 each and non-steered test types being repeated 5 times and to allow for variance resulting from different evacuation plans produced by MSR steering. This repetition would allow any anomalous results to be detected. Each of the 20 different initial conditions varies in initial fire location and the starting location of each occupant. The number of occupants in each different initial condition was varied with there being an average of 95 (range 78 - 109) across 19 of the 20 scenarios with a significantly larger outlier of 246 occupants. This was to determine how the system would cope with a much larger number of people.

The following data was taken from each simulation:

- Total FED for all occupants.
- Total evacuation time.
- Time for 50% of total initial population to have evacuated building.

Two distinct sets of possible initial fire locations were considered and these are defined in Figure 3-2 and will be referred to as location set 1 and location set 2 throughout the remainder of the chapter. The two different sets were chosen to represent a varied challenge for egress route selection and although there are different discrete locations within each location set, such fires will result in similar effects on egress routes. Out of the 20 different scenarios; 15 consisted of fires in location set 1 and 5 in location set 2. This difference was justified by the fact there are more possible discrete locations in set 1 than set 2. These all comprise fires in corridors, rather than rooms. Justification for not including room fires here was that it was necessary to use a hazard that would spread as quickly as possible, to provide a challenging environment for the DRPS. Room fires would be likely to create a hazardous location in the compartment of origin, but due to generally low egress path lengths, this would not spread in time to provide a sufficiently challenging environment elsewhere.

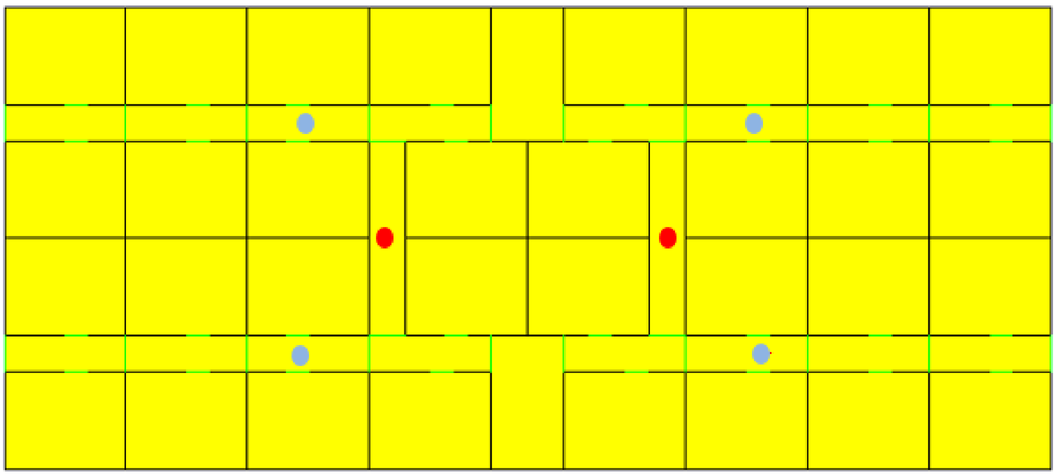

Figure 3-2 - Possible Fire Locations - Blue dots refer to location set 1 fires and red dots to location set 2 fires.

A stack of papers was chosen as the burning item of choice for all experiments due to the fast growth rate of the ensuing fire. This will result in smoke being able to rapidly impact upon egress routes although the maximum heat release rate (HRR) and smoke production was relatively low. Despite this fire having given very low overall FED results it is still valid to compare between the various test types.

Upon initiation of a simulated evacuation the following assumptions were made:

- Once an occupant has evacuated the building they will not attempt to re-enter.
- It is impossible for alarms to malfunction.
- All occupants are considered to be awake from the beginning of the simulation.

3.3 Test Type Explanation

A variety of test types were utilised to demonstrate the potential benefits of occupant steering in terms of evacuation safety. These include both steered and un-steered with varying levels of occupant obedience.

Dynamic Steering - Upon an alarm being activated, a set of path instructions are generated using the sensor data available at that time. These instructions are revised at certain time intervals for the duration of the simulated evacuation to respond to the evolving scenario. Multiple execution run.

Static Steering - Upon an alarm being activated, a set of path instructions are generated using the sensor data available at that time. These are not updated for the remainder of the evacuation. Single execution run.

Obedience Rating - Defined as the percentage of occupants that are considered to adhere to the DRPS instructions. This is to represent the likelihood of occupants misunderstanding or simply ignoring instructions, in real world evacuations. Which occupants are defined as disobedient is determined randomly at the beginning of each simulation. These disobedient occupants will adhere to standard CRISP behavioural rules as if they were in an un-steered evacuation (described below), except that they are defined as "alert". Occupants that are defined as disobedient, remain so for the duration of the simulation.

Alarm Activated Evacuation (AA) - No path instructions are sent to the occupants but upon an alarm being activated all occupants have their actions set to "escape" and target room set to "outside". The path which the occupant takes is defined by the CRISP behavioural and route finding rules. The purpose of this test type is to remove the difference in pre movement time between steered and un-steered evacuations, thus allowing focus on comparing occupant selected routes with DRPS selected routes. Disobedience within AA tests means that the CRISP action is not changed to "escape".

Un-steered - No alterations to basic CRISP model other than the assumptions described (can carry out any CRISP action, other than sleeping).

3.3.1 Not steered by DRPS

- Totally un-steered.
- Alarm Activated Evacuation, 100% Obedience
- Alarm Activated Evacuation, 75% Obedience
- Alarm Activated Evacuation, 50% Obedience
- Alarm Activated Evacuation, 25% Obedience

3.3.2 Steered by DRPS

- Dynamic Steering, 100% Obedience
- Dynamic Steering, 50% Obedience
- Static Steering, 100% Obedience
- Static Steering, 50% Obedience

It should be noted that pre-movement time is only considered for occupants in totally un-steered simulations and occupants that are defined as disobedient in the remaining tests. Obedient occupants in AA and steered tests will commence egress immediately upon being instructed to evacuate. To summarise the above: dynamic and static steered occupants have their CRISP actions changed and target rooms changed in accordance with the DRPS plans; AA occupants only have their action changed and their target room set to outside and un-steered occupants have nothing changed. Disobedient occupants in all tests have neither action nor target room changed. All the occupants in every test are defined as alert, from the moment the alarm is triggered. Dynamic and static tests are all multiple solution executions (MSR) in this chapter, with 100 solutions being generated each time.

3.4 Results and Discussion

To determine the potential benefits of an intelligent egress system and its component parts, it is necessary to compare FED levels resulting from steered and non-steered tests. In addition, the most crucial comparisons to make across the variety of tested scenarios are as follows:

- The difference between dynamically and statically steered simulations of equal obedience levels
- The influence of varying obedience levels.

Further comparisons were made to determine if initial fire location and total population affected the overall trends. The median population across the tests, excluding the one with a far greater number of occupants, was 95. Results from those with populations above and below that number were compared separately. The total FED was summed across all occupants for each simulation, with "average total FED" representing an average of all of these totals FED values, for each test type. The overall FED results are shown in Table 3-1, Figure 3-3 and Figure 3-4.

Average Total FED for all Scenarios					
Test Scenario Type	**ALL**	**Population > Median**	**Population < Median**	**Fire Location 1**	**Fire Location 2**
UNSTEERED	1.06	1.13	0.82	0.69	2.17
AA 100%	0.26	0.37	0.18	0.34	0.00
AA 75%	0.29	0.38	0.22	0.33	0.19
AA 50%	0.32	0.37	0.24	0.31	0.32
AA 25%	0.39	0.44	0.32	0.35	0.51
DYNAMIC 100%	0.06	0.05	0.07	0.08	0.00
DYNAMIC 50%	0.17	0.14	0.18	0.16	0.20
STATIC 100%	0.06	0.06	0.06	0.07	0.00
STATIC 50%	0.17	0.16	0.15	0.15	0.23

Table 3-1 - Average Total FED for all Scenarios

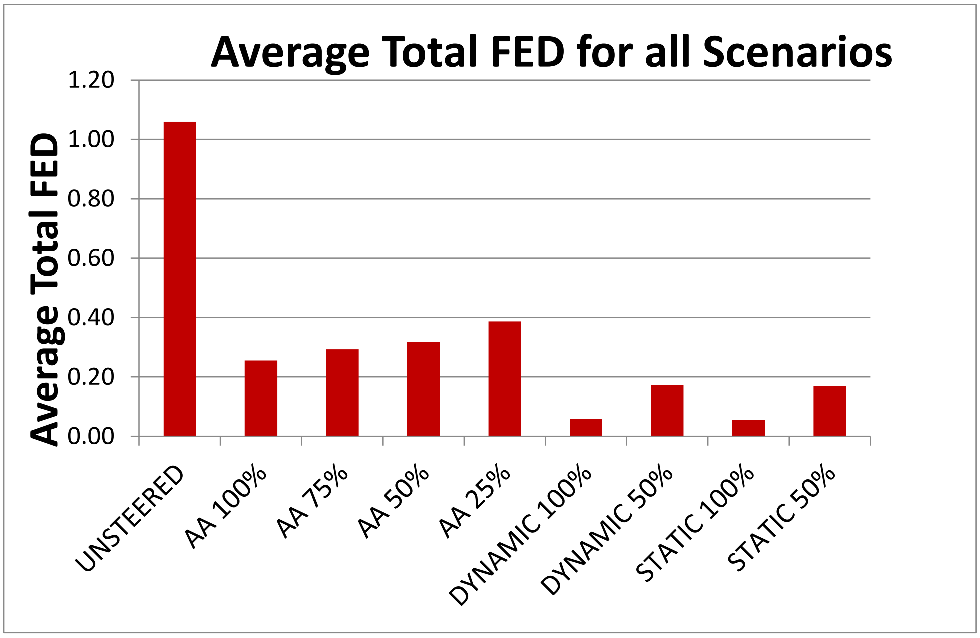

Figure 3-3 - Average Total FED for all Scenarios

In summary; totally un-steered tests resulted in the highest overall FED by a substantial margin when compared to all other test types, and across all different scenarios. Steered tests also resulted in lower FED values than non-steered tests in the majority of cases. For all alarm activated (AA) and steered tests, increased obedience levels resulted in a decreased total FED. The overall differences between static steered tests and dynamic steered tests are immaterially small, although there are some small but noticeable differences in certain scenarios. Overall, static steering provided lower FED results than dynamic. Some of the results, throughout the thesis, are also displayed as box pots (e.g. Figure 3-4), which show the spread of results for each test type, The box plot results for each test type show 5 different statistical values, in ascending order: Minimum, lower quartile, median, upper quartile and maximum. Blue boxes represent the quartiles, with the median value being the line within this box. Minimum and maximum values are shown by the single lines extending from the bottom and top of the box, respectively. Such a spread of results for each test type is likely to occur for several reasons. There are 20 different initial condition sets, meaning a different number of occupants will initially be in close proximity to the hazard. During tests with disobedient occupants, as the particular occupants which are disobedient are randomly selected each simulation, a spread of results is expected. Unsurprisingly, tests with a lower level of obedience have generally produced results with the greatest range, compared with similar test types with higher obedience. MSR steering will also have had an impact in creating a range of results as the chosen solution for each system execution, for one simulation, is unlikely to be the same as for other simulations.

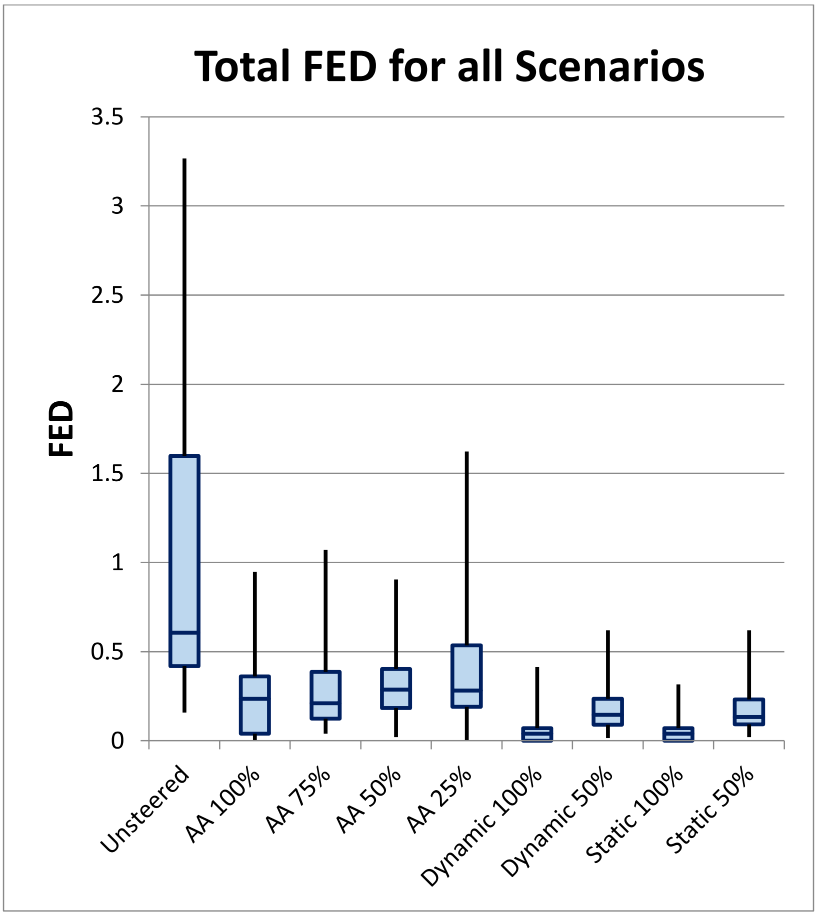

Figure 3-4 - Total FED for all Scenarios

Variations in the initial fire location had a profound effect on overall FED results, the specifics of which can be seen in Figure 3-5 to Figure 3-8. All test types with 100% obedience (including AA) returned a 0 average total FED for location set 2 fires. On the other hand totally un-steered tests with location set 2 fires resulted in substantially higher FED values than those in location set 1. For AA tests with location set 2 fires there was no trend relating to obedience with each rating producing very similar FED results. As expected, location set 1 fires resulted in an increasing FED trend with decreasing obedience. Static and dynamically steered tests with 50% obedience compared unfavourably to 100% obedience tests in both cases although the discrepancy was greater with location set 2 fires.

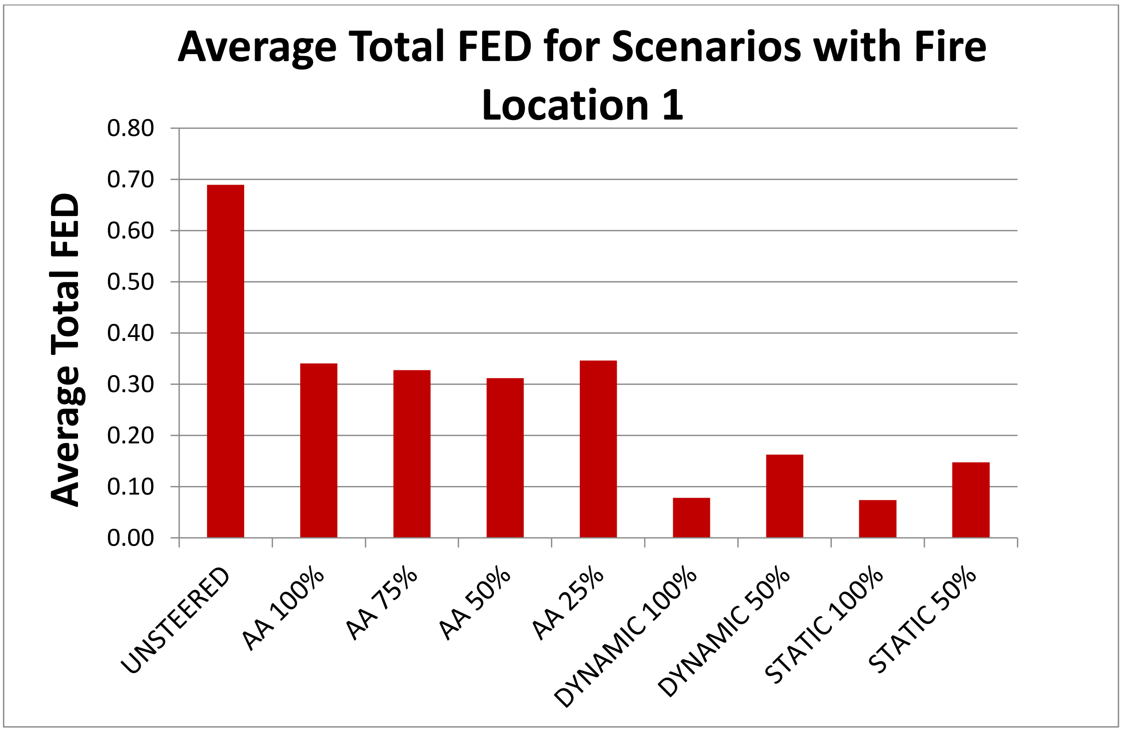

Figure 3-5 - Average Total FED for Scenarios with Fire Location 1

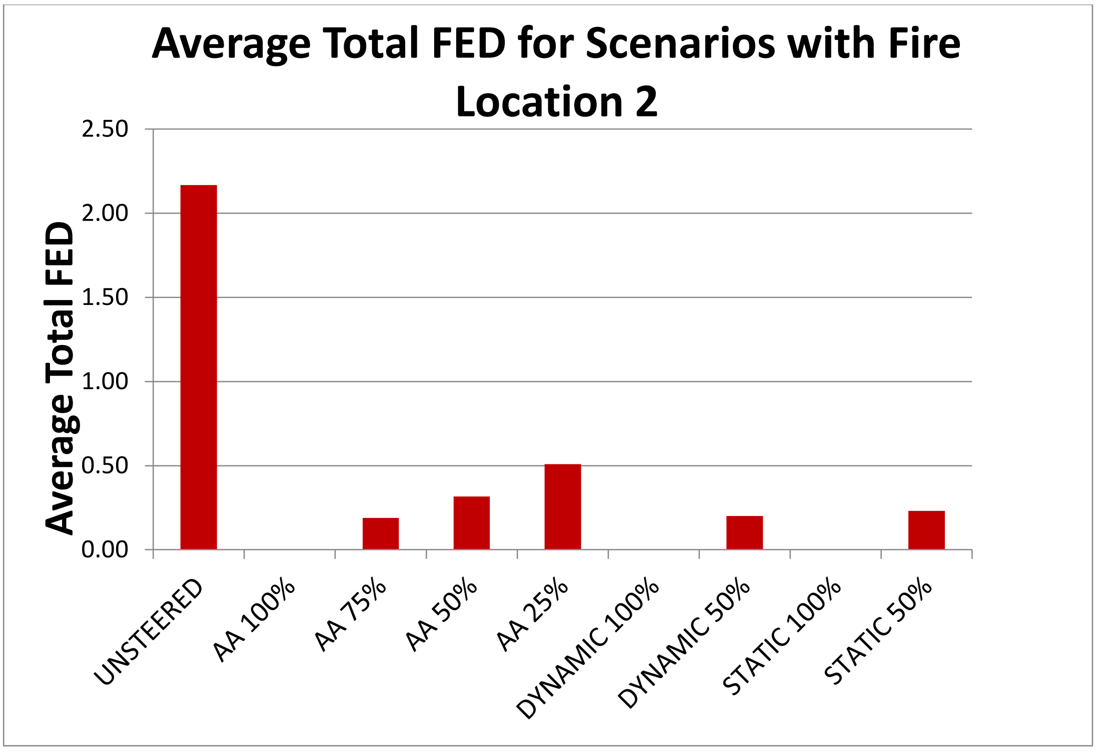

Figure 3-6 - Average Total FED for Scenarios with Fire Location 2

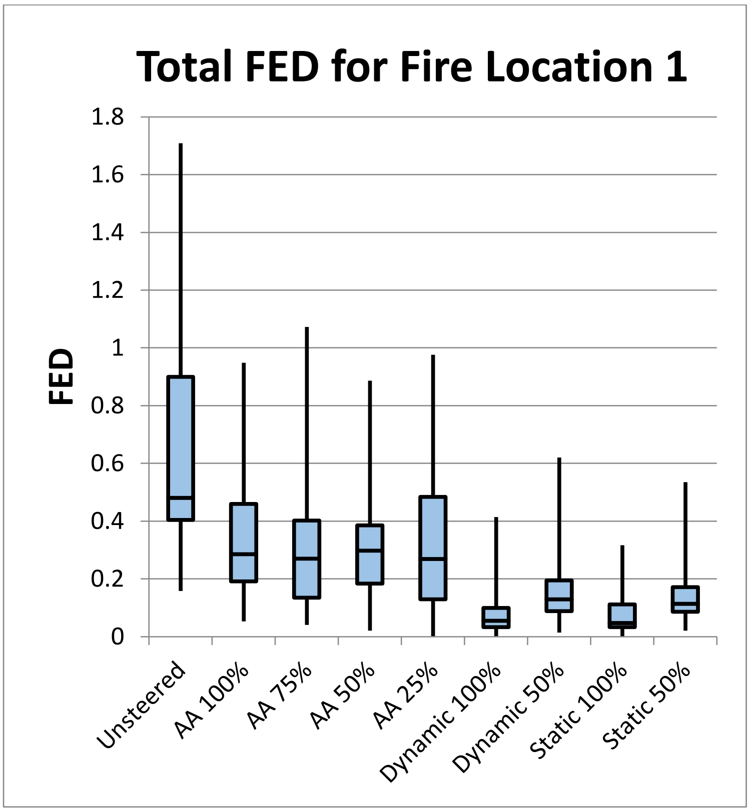

Figure 3-7 - Total FED for Fire Location 1

An obvious explanation for the all 100% obedience tests resulting in 0 FED values for location set 2 fires is that the hazard effected corridor sections are never required as part of an egress route from any room. This is because there are no rooms with doors that lead into this section of corridor, thus resulting in no occupant ever being directed along a path that comprises the hazardous compartment. Moreover the overall evacuation times are short enough for egress to be completed without significant FED causing smoke and toxins reaching occupants that may be queuing for exits. This argument is reinforced by the scenario with the highest population still producing 0 FED results despite having a higher total evacuation time.

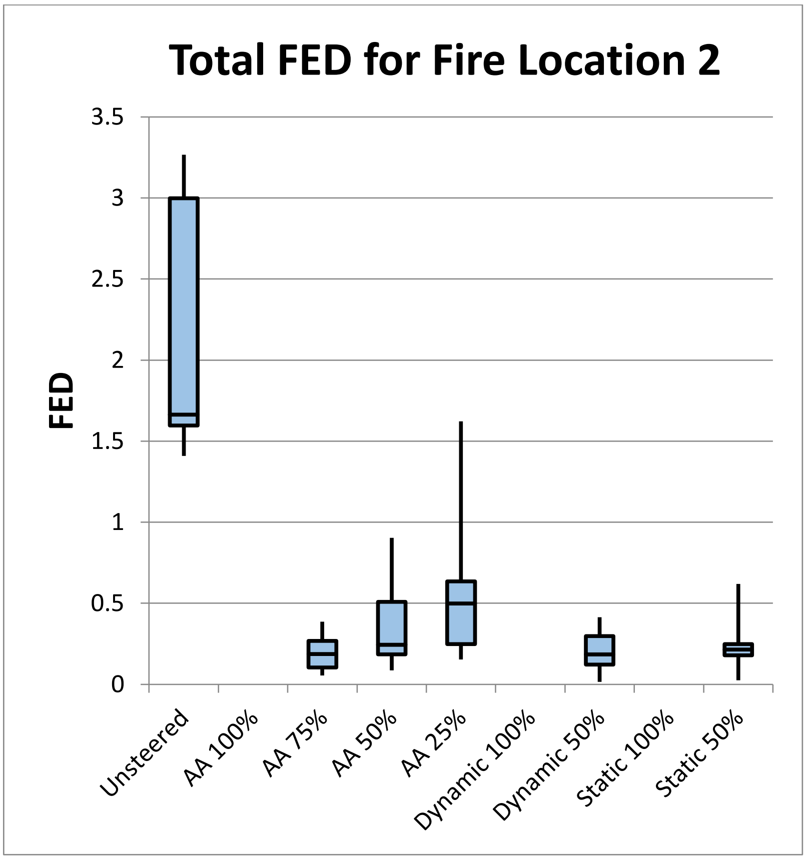

Figure 3-8 - Total FED for Fire Location 2

Occupants in AA 100% tests will have avoided the hazardous compartment because the shortest path to an exit will never have utilised this section of corridor. During totally un-steered and lower obedience tests it is likely that some occupants will have spent time in the compartment of fire origin. This is possibly down to the relatively low HRR of the fire not creating an environment that is perceived as adequately dangerous by the occupants at an early stage in the simulation. Several occupants are likely to have investigated the fire in this situation. However as the scenario develops, due to the high growth rate of the paper fire, an occupant may find themselves in a relatively dangerous situation that had initially been identified as benign, upon entering the room. This is magnified by the fact that the location set 2 fires occur in long corridor sections so an occupant at this location could be exposed to hazard for a significant length of time after realising that the compartment was less tenable than when they originally entered.

For location set 1 fires, none of the test types returned 0 FED results. This can be attributed to the fact that there are always a number of occupants who must pass through the corridor section containing the fire. For example when the fire is outside a room with only one exit - Figure 3-9 (windows were not considered in this building layout). AA (100% and 75% obedience) tests are likely to have resulted in higher FED values for location set 1 fires due to the possibility of the shortest path available to an occupant utilising the hazardous corridor section. In early fire development stages the compartment may not be deemed dangerous enough to require selection of an alternative path but this could rapidly change while the occupant is in transit due to the fire type.

Comparatively lower FED results for totally un-steered tests in location set 1 fire scenarios are likely because the fire is initially visible to a larger number of occupants as there are populated rooms which lead directly onto the corridor where the fire is located, which was not the case with location set 2 fires. The effect of being caught in a long corridor section with few possible exits, as with location set 2 fires as described above, is also not as relevant.

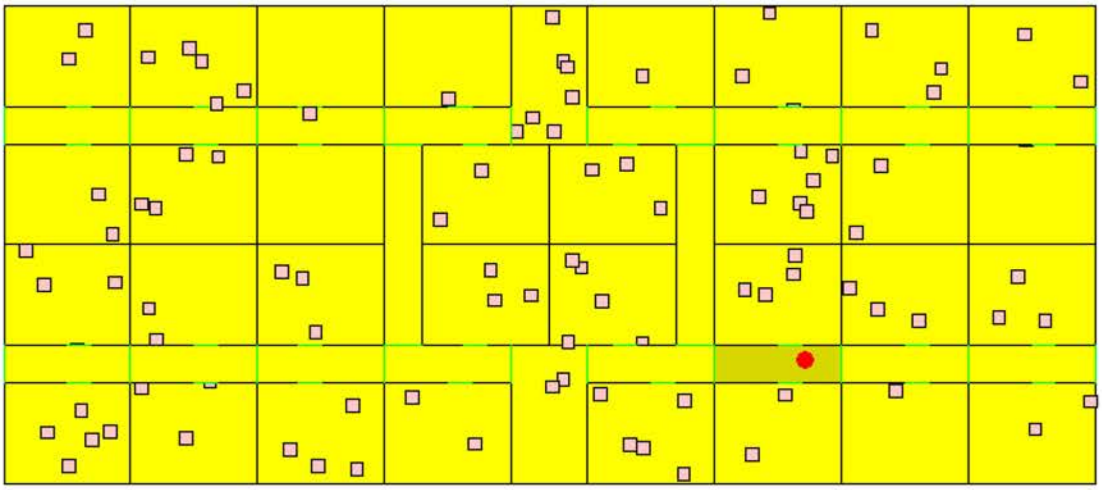

Figure 3-9 - A total of 6 occupants inhabit rooms from which the only path to safety is through the room of fire origin. Note that if the burning object was changed to one that would produce a more dangerous fire then evacuation from these rooms may not have been possible.

The combination of these conflicting factors affecting AA and un-steered tests is a possible explanation as to why the varying obedience levels within AA tests have little influence over the FED results of location set 1 fire scenarios. The disobedient occupants will be safer on average in location set 1 fires and the obedient occupants will be less so due to the shortest path being able to utilise the hazardous corridor section.

The median population across all scenarios, excluding the single scenario with a far greater number of occupants, was 95 and the results related to varied population are shown in Figure 3-10 to Figure 3-13. Of the 9 scenarios with populations of greater than the median only 2 were comprised of location set 2 fires, which is lower than the overall representation. Therefore there was a higher relative representation of location set 2 fires in scenarios with a lower population. As expected, the scenarios with a higher population returned higher Total FED results overall for non-steered test types which is likely due to the higher number of occupants being exposed due to the resulting higher population densities.

For dynamically steered tests (both 100% and 50% obedience), the scenarios with a higher population returned noticeably lower FED results than those with lower populations. However, when comparing Figure 3-12 and Figure 3-13, taking into account the relative position of quartiles, it would appear that there is a single outlier giving the greater maximum value for dynamic steering, compared with static. This applies to both 100% and 50% obedience levels and is therefore likely the result of a single initial condition set, which could explain this trend. The effect of population size on the static tests appears insignificant. It is possible that this outlier is also a factor responsible for the slightly higher overall FED values for dynamic steering, than for static steering. AA tests show a differing effect of obedience levels depending on total. There appeared to be very little difference between FED results across varying obedience levels for high population scenarios whereas there was a more expected linear increase in total FED for lower population scenarios.

When considering the combined effect of population size and fire location on total FED values it is possible to conclude that initial location is the dominant factor here. As the ratio of location set 1 and 2 fires within each population category are unequal, it is possible to attribute at least a greater proportion of the trend differences in each of these categories to fire location.

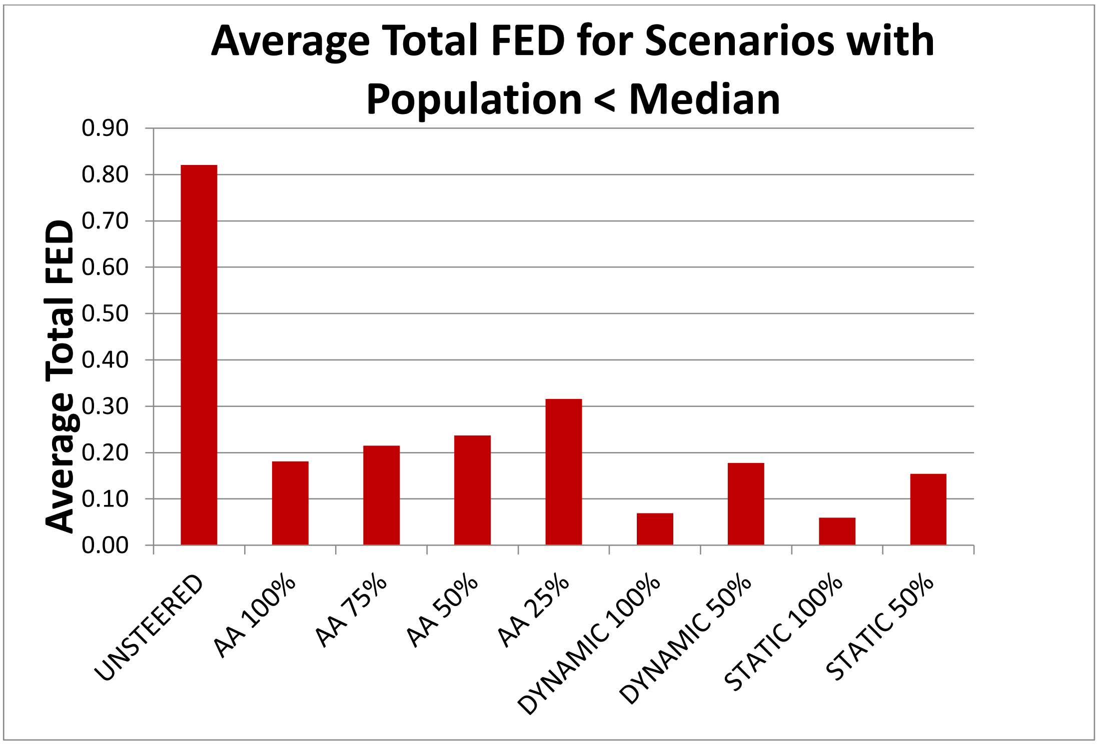

Figure 3-10 - Average Total FED for Scenarios with Population < Median

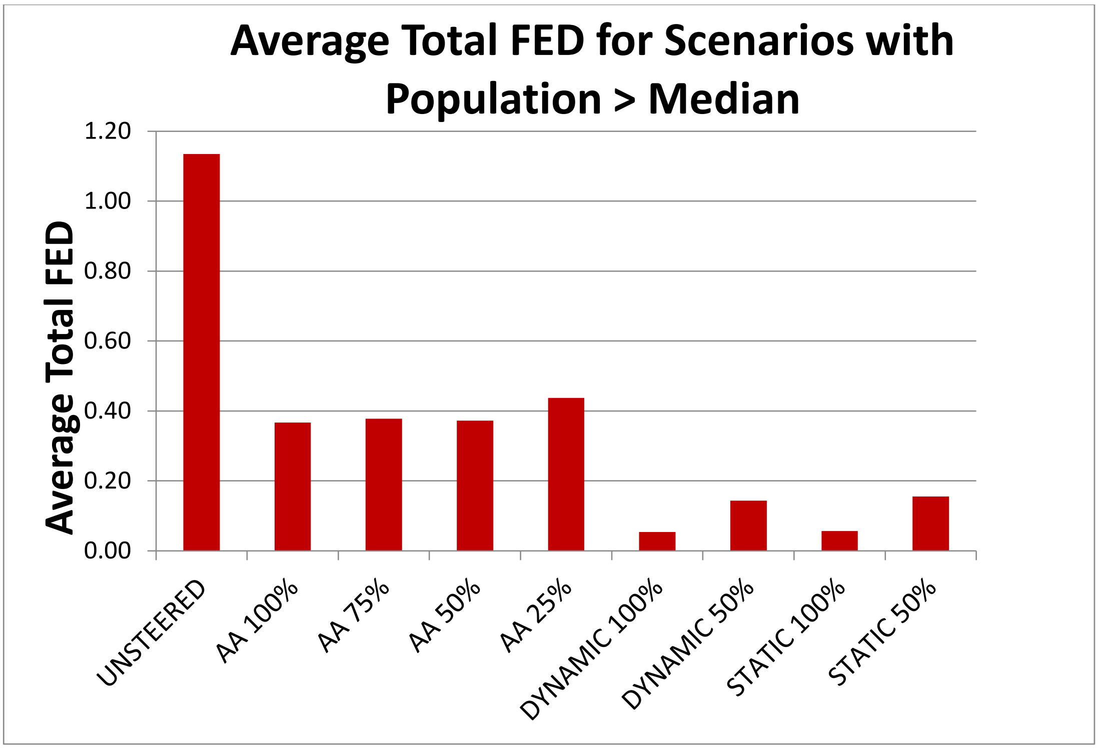

Figure 3-11 - Average Total FED for Scenarios with Population > Median

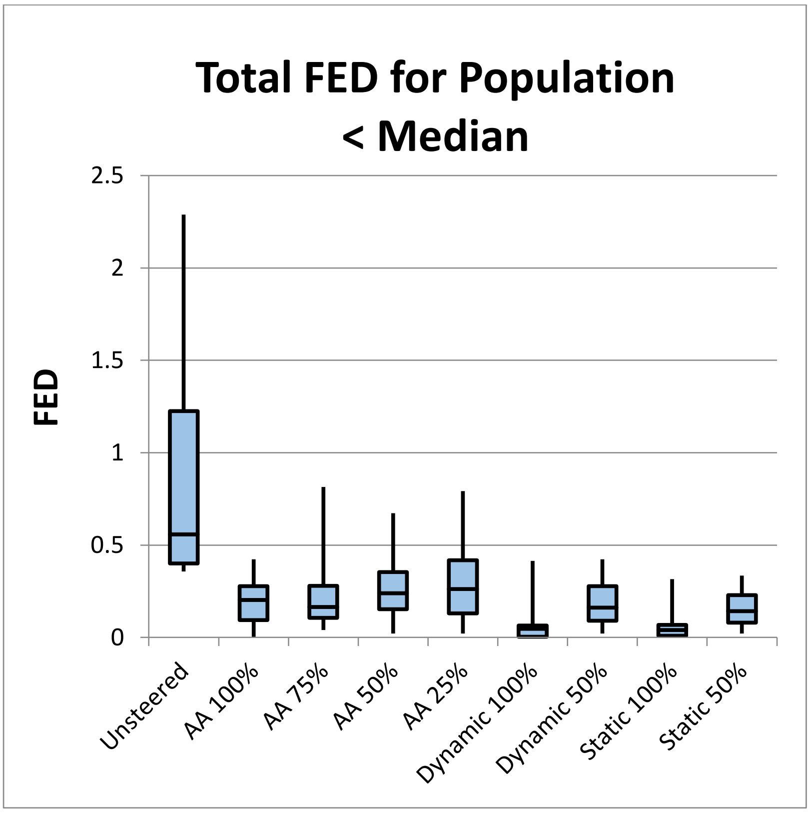

Figure 3-12 - Total FED for Population < Median

In terms of overall evacuation time (Figure 3-14 and Figure 3-15), totally un-steered tests consistently required longer than all other types, although dynamically steered tests consisted of the most varied times. Occupants in AA tests were consistently faster in completing egress than in steered tests. This can be attributed to occupants nearly always utilising the shortest available egress path when their action is set to escape, and end room to outside, because of the relatively small fire involved. As expected, the lower the obedience level for AA tests, the longer time required to complete egress. Dynamically steered tests required more time to complete than statically steered tests, with 50% obedience tests of both steering methods resulting in faster evacuations compared to the 100% obedience. It is clear from this and the FED results that a selection of the occupants that are disobedient are simply following the shortest path as per in AA tests.

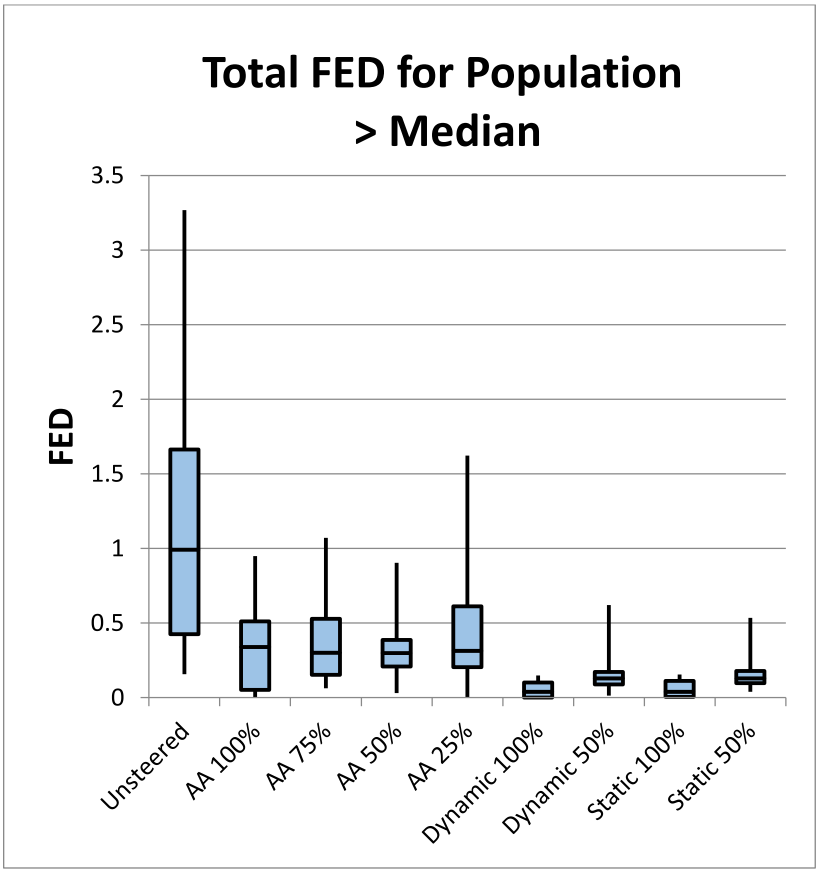

Figure 3-13 - Total FED for Population > Median

The slower nature of dynamically steered tests, compared to static steered tests, despite the overall FED results being very similar, can be accredited to specifics of the building layout as well as a functionality issue with the DRPS. It should be noted that the DRPS, at the stage of testing the single floor building scenario, did not include conservation of occupant travel direction from one system execution to another. This is likely to have resulted in occupants who have a selection of safe paths to choose between, having their route instructions constantly changed and this was the reason this functionality was added to the DRPS. This issue could have been amplified by the symmetrical nature of the building layout. For example there was often more than one equally safe, equidistance path to outside the building. A likely effect of this issue is that dynamically steered tests will have required more time to complete, which is as occurred. When comparing FED values with total evacuation times it can be concluded that time alone is not a good indicator of safe egress in these circumstances. Despite the issues with the DRPS regularly changing the direction of an occupant's instructed path, steered tests still resulted in the safest evacuations.

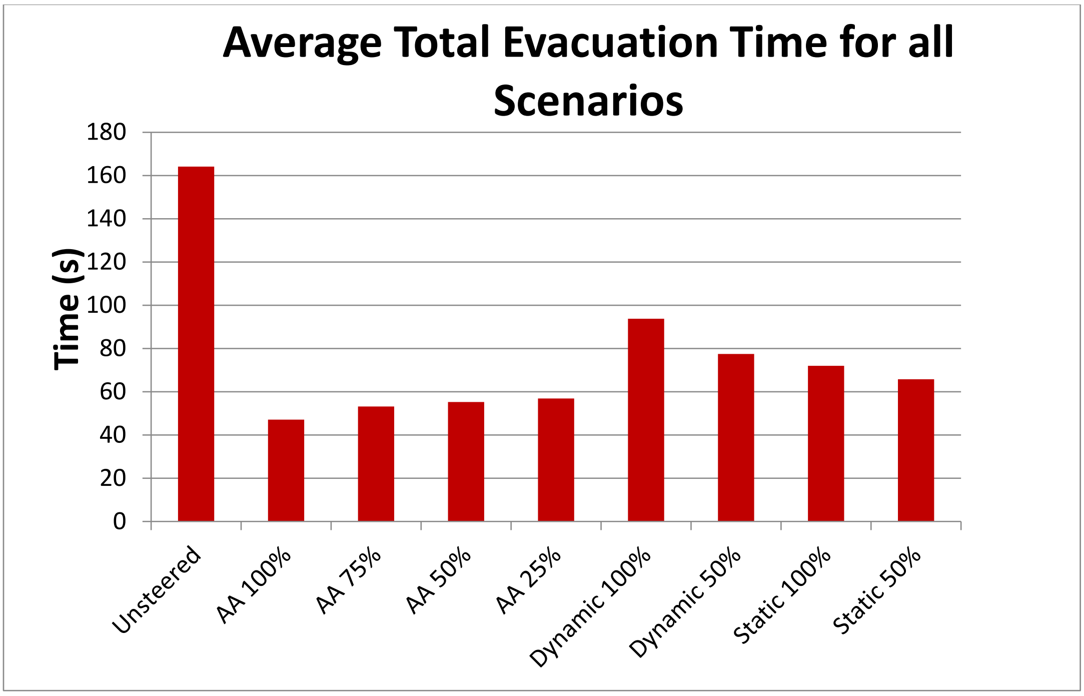

Figure 3-14 - Average Total Evacuation Time for all Scenarios

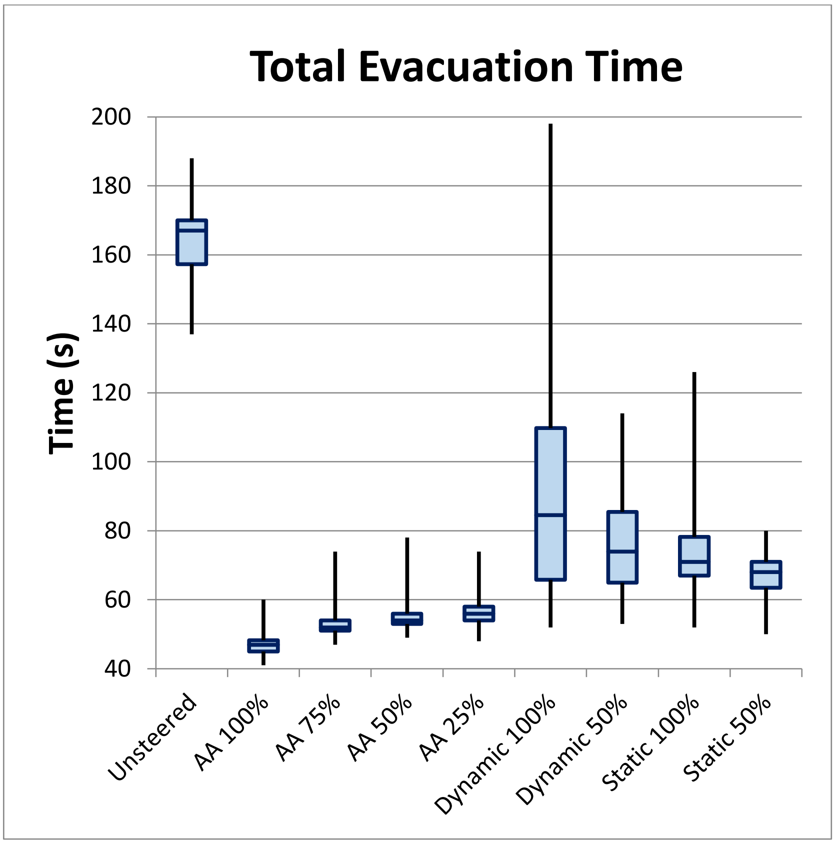

Figure 3-15 - Total Evacuation Time

The time required for 50% of the initial occupancy to evacuate the building gave slightly different trends to that of total evacuation time (Figure 3-16 and Figure 3-17). Totally un-steered tests remained the slowest by far and AA 100% remained the fastest but only marginally. All steered tests resulted in very similar 50% evacuation times with static proving slower to this point than dynamic although not significantly so. The most noteworthy differences between this and the full evacuation times is that AA tests aren't significantly faster than steered tests and the impact of obedience on steered tests is significantly smaller. The likely reasons for the lesser differences between steered and AA test types is that greater than 50% of the initial occupancy will be close to an exit therefore giving them an obvious choice. When considering this, if an average 50% of the occupants with a seemingly obvious exit choice follow the pattern of totally un-steered occupants, then decreased obedience would increase time for 50% of the occupancy to evacuate, which is as the results suggest. As for total evacuation time; time for 50% of the occupancy to complete egress also shows little relation to overall safety when compared to FED results.

These evacuation time results have given evidence for the importance of reducing unnecessary direction changes in occupant route instructions. It is also possible that the resulting discrepancy in total evacuation time could be responsible for static steered tests producing ever so slightly lower FED results than dynamic tests, where the increased system sophistication provided by the dynamic tests was expected to reduce FED levels. However, it is likely that the outlier discussed earlier in the chapter is a more significant factor here. Nevertheless, this result provides motivation for adding functionality (conservation of path direction - section 2.3.4) to the DRPS to restrict direction change and after such adjustments are made it is expected that dynamic steering will produce safer evacuations than static steering.

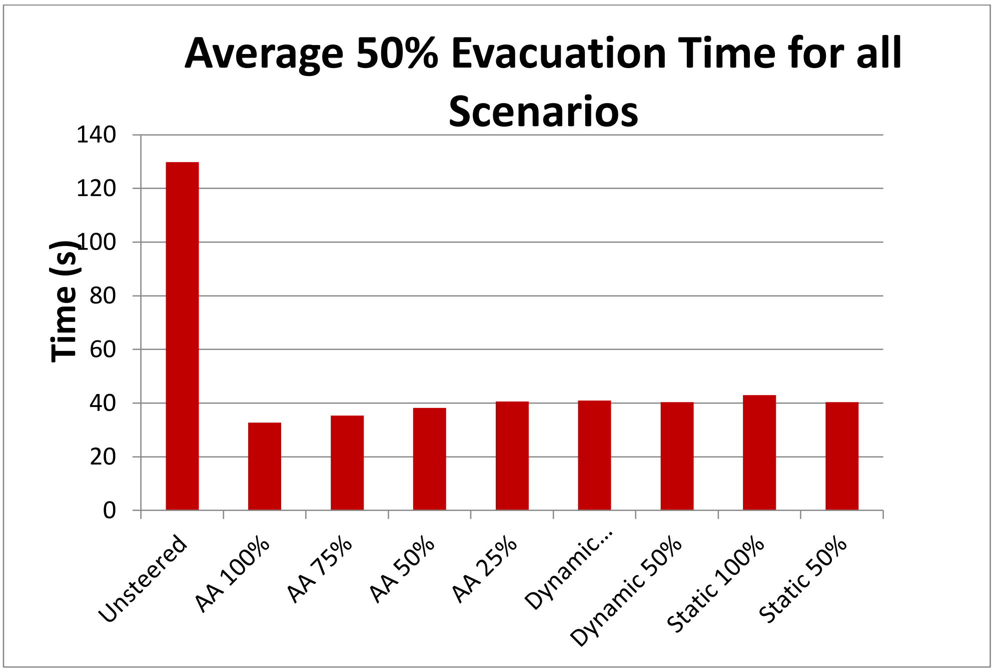

Figure 3-16 - Average 50% Evacuation Time for all Scenarios

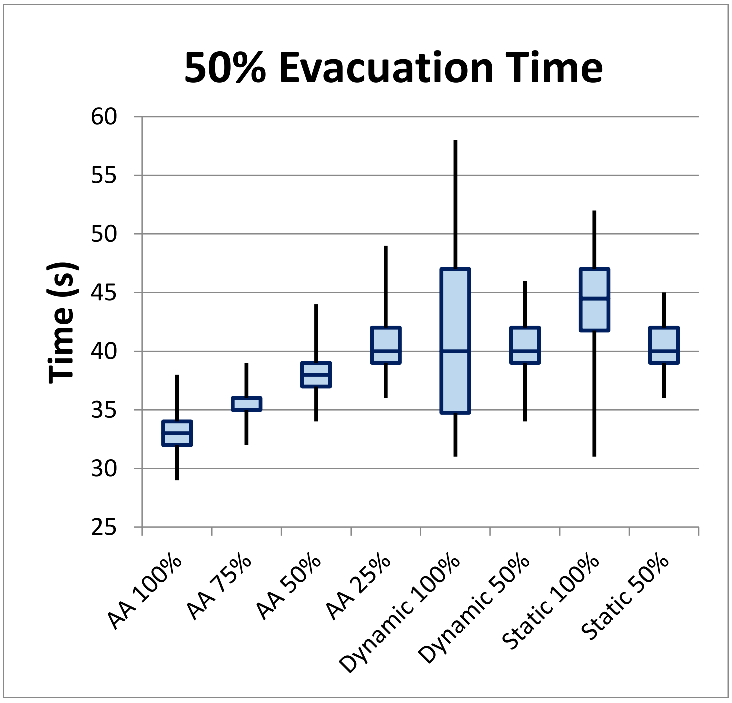

Figure 3-17 - 50% Evacuation Time. Totally un-steered results omitted from this chart to show other test results more clearly.

In conclusion, occupant steering resulted in an overall improvement in evacuation safety when measuring FED rather than egress time. It is an especially positive result in terms of demonstrating the potential benefits of such a system that both 50% obedience steered tests resulted in safer evacuations than AA 100% tests. This comparison is important because misunderstanding or ignoring of route instructions is highly likely to occur in real events and if occupants simply following the shortest available path to them resulted in safer evacuations, this would undermine the potential of the system.

It should be noted however that the results in this chapter can only play a small part in the necessary demonstration due to a number of factors. The building layout used in this scenario has limited realism, for reasons such as having no windows and the initial occupant locations, which relate to room type, being indiscriminate regardless of position within the building. For example, an office building is likely to have fewer occupants in windowless rooms where none of the walls contact the outside of the building.

In addition, the choice of burning object didn't produce particularly dangerous environments, and the resulting FED levels are all very low. However due to the consistency inherent with simulations it was still possible to obtain measurably different FED results between the various test types, and compare these in relative terms. For use in subsequent scenarios and the next stage in the development of the system it was necessary to use burning objects that have a much higher peak HRR and total burning time, and as such will produce a more hazardous environment, resulting in a greater range of FED levels. More serious fires will also influence the way in which occupants will respond. For example, they are more likely to initiate escape at an earlier point in time after they have become aware of the fire, as it is more likely to be deemed sufficiently dangerous. Larger, slower burning objects (e.g. a sofa) will likely provide a much more dangerous fire but will also grow more slowly than a paper fire. If such an item was used in this building layout however, due to the very low overall evacuation times, it may have not provided a testing enough environment for the DRPS to show any benefit as the majority of occupants could have exited or be very near an exit before conditions became sufficiently hazardous at any location.

All tests in this scenario comprised fires located in corridor sections. This allowed smoke to move quickly throughout the building creating as challenging a situation for the DRPS as was possible given the nature of the building and fire. It is more likely however that a fire will start in a room instead, due to the increased fire load density but this was not chosen for this scenario for the same reasons as choice of burning object. When a more complex building was considered in later chapters, room based fires were more appropriate as overall evacuation times were greater due to increased egress path length. It is expected that the higher complexity of a building, the more advantageous such a system will be. This is because there will be a lower proportion of occupants in direct line of sight of the hazard and as such the shortest, safest path will not always be apparent. This situation is most likely to occur in a multi-floor building and this is the subject of the next chapter.

4 Multi-Floor Building Scenario

This chapter demonstrates the dynamic route planning system being applied to a more complex three floor building with a greater number of occupants and rooms than in the previous chapter. It has been hypothesised that such an intelligent egress system is likely to have greater benefits to overall evacuation safety, the more complex the building and evacuation routes are. Moreover, the required level of sophistication that the system should adopt to obtain the most favourable results was expected to increase with greater scenario complexity.

4.1 Scenario Description and Test Method

The building layout used in this chapter (Figure 4-1) is of a similar design to that in chapter 3 with the two floors being added. Stairwells that connect the ground to 1st floor are room numbered 105 and 106 and those which connect the 1st to 2nd floor are rooms numbered 87 and 94. The remaining room type allocations are as follows:

- Office:
  - Ground Floor: 1-4, 6-12, 15-20, 23-29, 31, 34.
  - 1st Floor: 53-56, 58-61, 63, 64, 67, 68, 70-72, 75-81, 83-86.
  - 2nd Floor: 107-117, 120-123, 126-136.
- Stores:
  - Ground Floor: 13, 14, 21, 22.
  - 1st Floor: 65, 66, 73, 74.
  - 2nd Floor: 118, 119, 124, 125.
- Open Spaces (All floors): 5, 30, 57, 62, 69, 82, 137, and 138.

The fire load for each compartment where fires were located was as follows:

- Offices: Sofa, waste paper bin, papers, T.V.
- Open Spaces (Note: fires in these locations are referred to as corridor fires)
  - Rooms 62 and 69: Sofa, waste paper bin, papers, T.V.
  - Rooms 5, 30, 57 and 82: Christmas tree and waste paper bin.

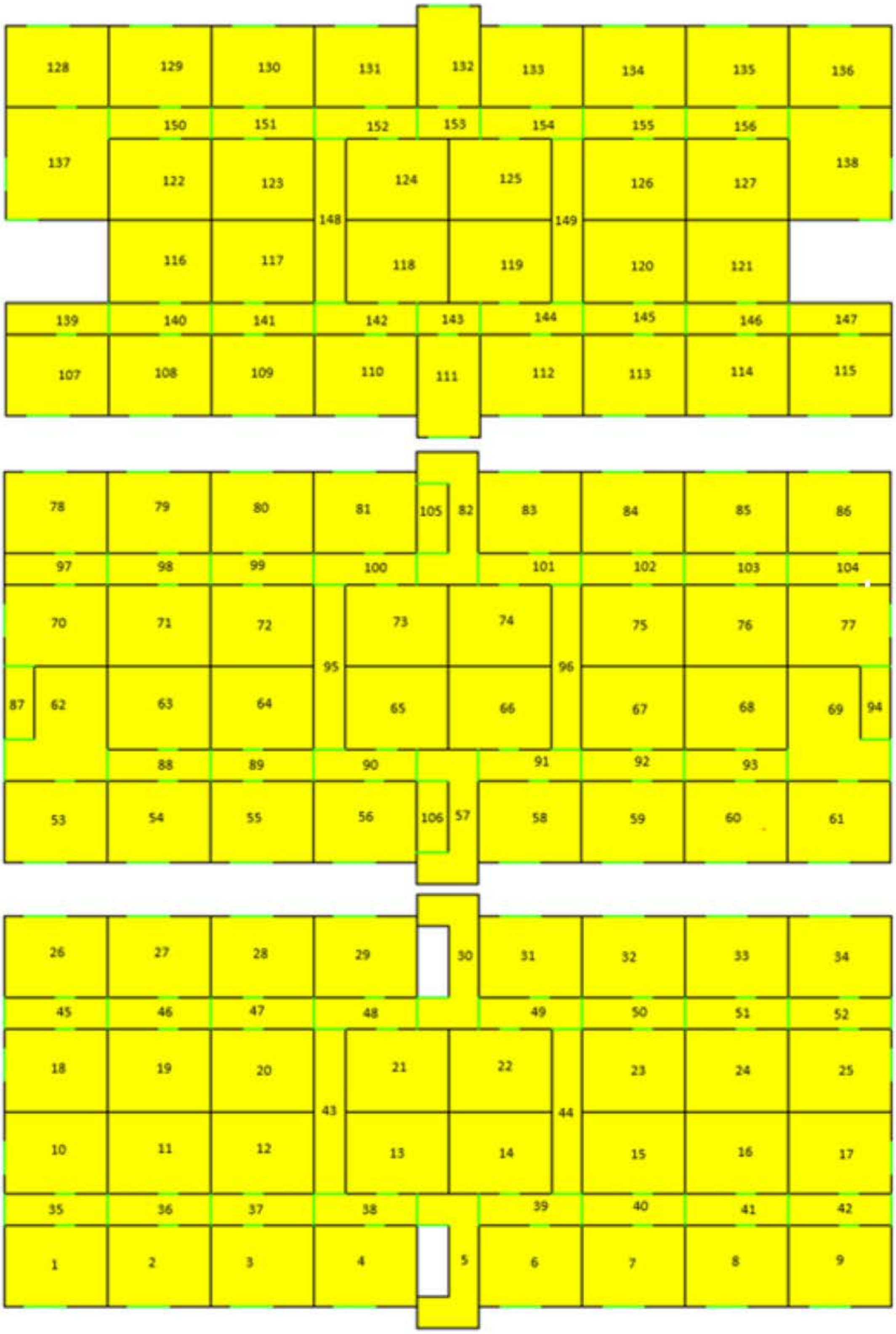

Figure 4-1 - 3-floor building layout with room numbers. From top to bottom the diagram shows the 2nd, 1st and ground floor.

Smoke detectors were located in the following corridor sections:

- Ground Floor: 36, 38, 39, 41, 46, 48, 49, 51
- 1st Floor: 57, 62, 69, 82, 89, 92, 103
- 2nd Floor: 140, 143, 146, 150, 153, 156.

The building layout used in this chapter has limitations relating to how realistic it is compared with real world structures. One significant limitation is that there is no continuous stairwell from the ground to second floor. Reasons that this building was used are that it was a relatively straightforward process to implement in CRISP, by building on the layout in chapter 3, as each floor was very similar, and a challenging, more hazardous environment would be easier to create. It was originally intended to have continuous stairwells but it was not possible without significant changes to the original floor plan. Despite these limitations, it is still valid for purposes of demonstrating the system's capabilities.

A total of 60 simulations per test type (described below) were carried out, which included 20 different initial condition scenarios, each repeated 3 times. This is necessary to reduce the impact of any single test, especially those generated by varying obedience and MSR testing. As was seen in the previous chapter, one outlier can change the overall trends. From each simulation the following data was extracted:

- Total FED for all occupants
- Maximum FED accrued by an individual occupant.
- Total evacuation time
- Time for 50% of total occupancy to have evacuated building

Each of the 20 different initial conditions varies in fire initial location, initial burning object and the starting location of each occupant. Half of these initial conditions have room based fires where the other half comprises corridor based fires. These different types of starting locations were chosen to give a variety of smoke spread, time to alarm detection and stairwell availability. In all room based fires the initial burning object is a sofa while corridor based fires comprise 50% sofa fires and 50% Christmas tree fires. The different types of corridor based fire were chosen to give two fires with very different growth rate and burning properties. Room based fires can start in any room that was defined as an office. Corridor based fires (actually in compartments defined in CRISP as “open spaces”) were divided into sofa fires and Christmas tree fires. Sofa fires were located in rooms 62 and 69 and Christmas tree fires were located in any of rooms 5, 30, 57 and 82.

Occupant initial locations are defined by having a 95% chance of being initially located within a room defined as an office and a 5% chance of being located within a store room, with each simulation consists of exactly 300 occupants initially inside the building. This results in an average of 15 occupants per simulation being located in the centre block of 4 rooms on each floor and the remaining 285 being evenly distributed throughout the remaining office defined rooms. No occupants would be initially located within a corridor section. The initial locations were equally distributed between rooms of the same type - there is no weighting on individual areas of the building to create an unbalanced population density.

When comparing the results from sofa and tree fires, only corridor based fires are considered. The floor distribution of initial fire locations was as follows:

- Ground Floor - 4 (20% of Total) of which 3 are room and 1 is a corridor based fires.
- First Floor - 14 (70% of Total) of which 5 are room and 9 are corridor based fires.
- Second Floor - 2 (10% of Total) of which both are room based fires.

This implies that nearly all corridor based fires are located on the first floor, while room based fires are more evenly distributed. More first floor fires were chosen because that is when the hazard is most likely to interfere with greatest number of egress routes. The justification for choosing relatively few fires originating on the 2nd floor is that the results from these aren't as interesting as those from lower floors. This is because, for steered evacuations, the FED results from 2nd floor fires are more likely to be determined by how many occupants' initial locations are close to the hazard, than the particular steering type.

Upon initiation of a simulated evacuation the following assumptions are made:

- Once an occupant has evacuated the building they will not attempt to re-enter.
- It is impossible for alarms to malfunction.
- All occupants are considered to be awake from the beginning of the simulation.
- Although windows on floors other than the 2nd can be used by occupants to evacuate, they are never considered in the DRPS and therefore will never be instructed to use them.

4.2 Test Type Explanation

This section describes the various test types that were used during simulated evacuations. Each steered evacuation is identified by a steering type, obedience rating, and the number of evaluated solutions per system execution, and whether cumulative movement data is being used.

Dynamic Steering - Upon an alarm being activated, a set of path instructions are generated using the sensor data available at that time. These instructions are revised at certain time intervals for the duration of the simulated evacuation to respond to the evolving scenario. Multiple execution run.

Static Steering - Upon an alarm being activated, a set of path instructions are generated using the sensor data available at that time. These are not updated for the remainder of the evacuation. Single execution run.

Obedience Rating - Defined as the percentage of occupants that are considered to adhere to the DRPS instructions. This is to represent the likelihood of occupants misunderstanding or simply ignoring instructions, in real world evacuations. Which occupants are defined as disobedient is determined randomly at the beginning of each simulation. These disobedient occupants will adhere to standard CRISP behavioural rules as if they were in an un-steered evacuation (described below), except that they are defined as "alert". Occupants that are defined as disobedient, remain so for the duration of the simulation.

Universal Fastest Path (UFP) - Each occupant is instructed upon the shortest available safe path. This will adhere to rules regarding conservation of path direction and priority, where possible. Single solution execution.

Multiple Solution Run (MSR) - The system will evaluate a defined number of solutions for each system execution, selecting the safest or fastest equal safest.

Alarm Activated Evacuation (AA) - No path instructions are sent to the occupants but upon an alarm being activated all occupants have their actions set to "escape" and target room set to "outside". The path which the occupant takes is defined by the CRISP behavioural and route finding rules. The purpose of this test type is to remove the difference in pre movement time between steered and un-steered evacuations, thus allowing focus on comparing occupant selected routes with DRPS selected routes. Disobedience within AA tests means that the CRISP action is not changed to "escape".

Un-steered - No alterations to basic CRISP model other than the assumptions described.

Speed Adjustment - The maximum movement speed on each node is adjusted as per data from perpetual occupant movement monitoring.

Working Area Adjustment - The working area of each node is adjusted as per data from perpetual occupant movement monitoring.

4.2.1 Steered by DRPS

- Dynamic Steering, 100% Obedience, Universal Fastest Path
- Dynamic Steering, 50% Obedience, Universal Fastest Path
- Static Steering, 100% Obedience, Universal Fastest Path
- Static Steering, 50% Obedience, Universal Fastest Path
- Static Steering, 100% Obedience, Multiple Solution Run
- Static Steering, 100% Obedience, Multiple Solution Run, Adjusted Speed and working areas (AS).

4.2.2 Not steered by DRPS

- Alarm Activated Evacuation, 100% Obedience
- Alarm Activated Evacuation, 50% Obedience
- Un-steered

The number of solutions generated in MSR runs was 100. Although it would be possible to generate far more solutions which in turn could produce safer path instructions, this would jeopardise the goal of achieving near real-time steering. Thus the advantages of utilising a higher number of solutions were not deemed sufficient. Near-real time, rather than real time, is the result of CRISP running slightly slower than real time due to the size of the sensor data files being continually created. This was discussed further in section 2.6. The DRPS still evaluated 100 solutions for MSR runs in 3 or 4 seconds. Pre-movement times in this chapter are the same as for chapter 3, as in, it is only a factor for totally un-steered and disobedient occupants.

4.3 Results and Discussion

To demonstrate the potential benefits of an intelligent egress system and its component parts, it is necessary for FED levels to be lower in steered tests than in non-steered tests. In addition, it would be expected that the more sophisticated attributes of the DRPS which are employed the greater the positive impact on evacuation success. The most crucial comparisons to make across the variety of tested scenarios are:

- The difference between dynamically and statically steered simulations of equal obedience levels.
- The effect of differing obedience levels.
- The difference between multiple solution and universal fastest path runs.
- The difference between steered and the various un-steered tests.

The total FED was summed across all occupants for each simulation, with "average total FED" representing an average of all of these totals FED values, for each test type. For each simulation, the FED value for the individual occupant that had received the highest dose was also recorded. The "average maximum individual FED", for each test type, is the average of these maximum values. The purpose of this additional value is to determine if doses for single occupants are significantly affecting the overall results.

Average Total FED for all Scenarios								
Test Type	**ALL**	**ROOM**	**CORR**	**SOFA**	**TREE**	**G**	**1ST**	**2ND**
DYNAMIC 100% UFP	2.99	1.97	4.01	6.14	1.89	1.44	3.86	0.01
DYNAMIC 50% UFP	7.88	2.14	13.63	20.81	6.44	2.49	10.55	0.02
STATIC 100% UFP	4.13	3.55	4.72	7.52	1.91	6.14	4.13	0.01
STATIC 50% UFP	7.04	6.64	7.43	10.10	4.75	10.26	7.11	0.11
STATIC 100% MSR	4.21	4.03	4.40	6.78	2.02	6.61	4.13	0.01
STATIC 100% MSR AS	4.31	4.08	4.54	7.06	2.02	6.47	4.31	0.05
UNSTEERED	13.82	11.46	16.18	24.43	7.93	17.26	14.76	0.29
AA 100%	49.19	11.02	87.36	2.85	171.88	19.96	64.17	0.30
AA 50%	28.26	10.53	46.00	28.66	63.33	17.54	34.93	0.31

Table 4-1 - All Total FED results

Average Maximum Individual FED for all Scenarios								
Test Type	**ALL**	**ROOM**	**CORR**	**SOFA**	**TREE**	**GROUND**	**1ST**	**2ND**
DYNAMIC 100% UFP	0.24	0.29	0.19	0.35	0.03	0.21	0.28	0.00
DYNAMIC 50% UFP	3.72	0.42	7.01	11.26	2.76	0.53	5.15	0.02
STATIC 100% UFP	0.23	0.24	0.22	0.40	0.04	0.40	0.21	0.00
STATIC 50% UFP	2.62	1.24	4.01	6.31	1.71	2.69	2.96	0.10
STATIC 100% MSR	0.23	0.21	0.25	0.40	0.11	0.32	0.24	0.00
STATIC 100% MSR AS2	0.24	0.21	0.28	0.44	0.11	0.29	0.26	0.00
UNSTEERED	4.69	1.93	7.45	11.88	3.03	4.42	5.43	0.10
AA 100%	4.80	1.95	7.65	0.20	15.10	4.58	5.52	0.10
AA 50%	6.77	1.43	12.10	15.99	8.21	3.38	8.67	0.10

Table 4-2 - All Individual FED results

FED Results for all scenarios are shown in Figure 4-2 to Figure 4-5.

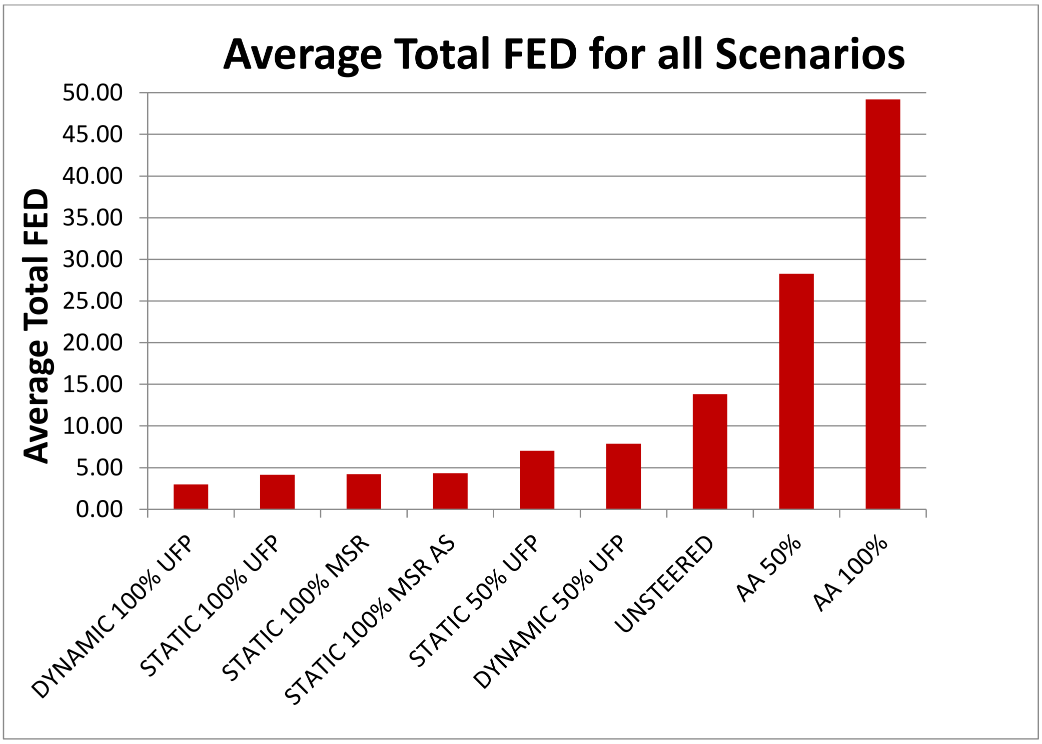

Figure 4-2 - Average Total FED for all Scenarios

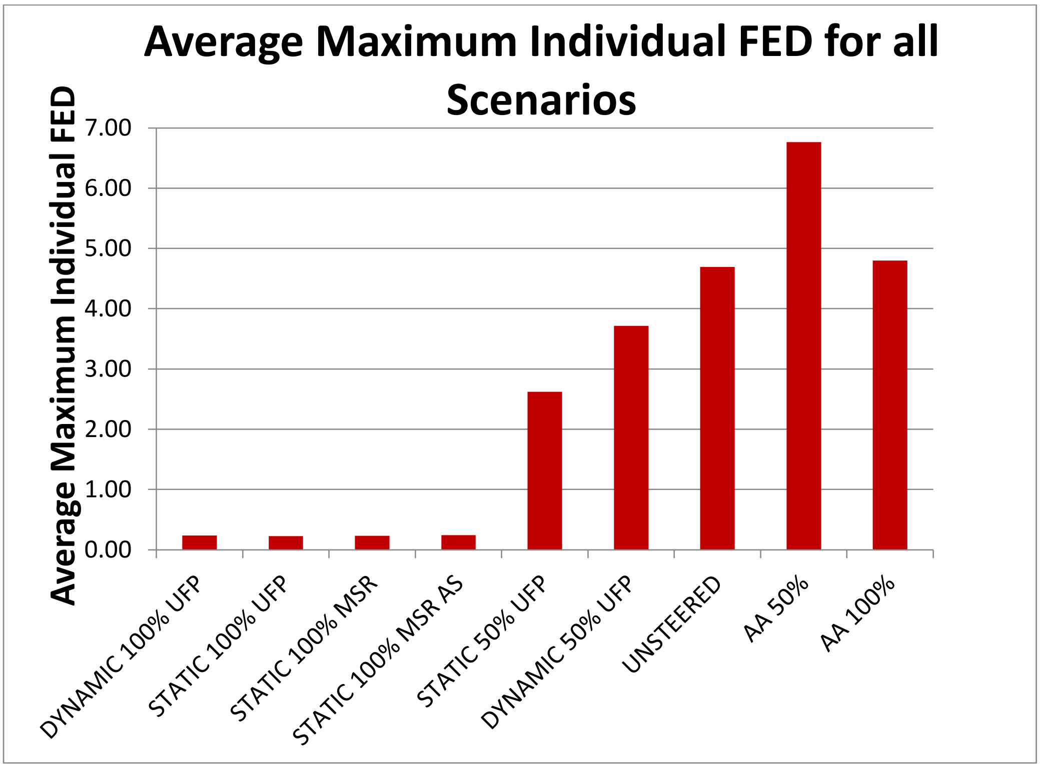

Figure 4-3 - Average Maximum Individual FED for all Scenarios

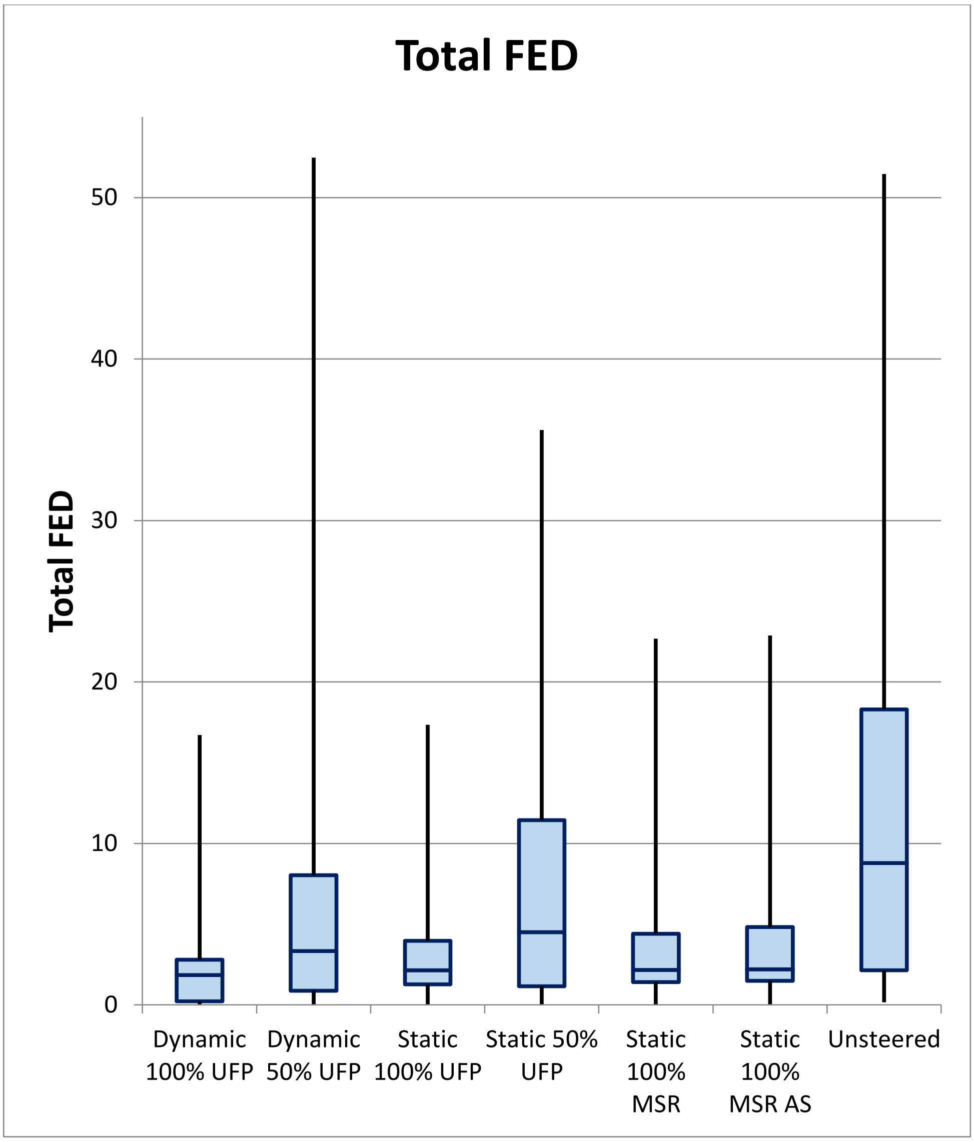

Figure 4-4 - Total FED

In summary room based fires proved to be less hazardous than corridor based fires, of which those that comprised a burning sofa produced higher FED results than burning Christmas trees. This outcome is as expected as smoke is more likely to permeate through greater proportions of a building if the fire is located within a section of corridor and the larger amount of burning material available on the sofa would be likely to create a more hazardous environment with a higher peak HRR and longer burning duration. It should be noted that the results of alarm activated evacuation (AA) tests have been omitted from some graphs as they often include significantly higher FED results than all other test types. This allowed a clearer comparison between more successful test types to be made.

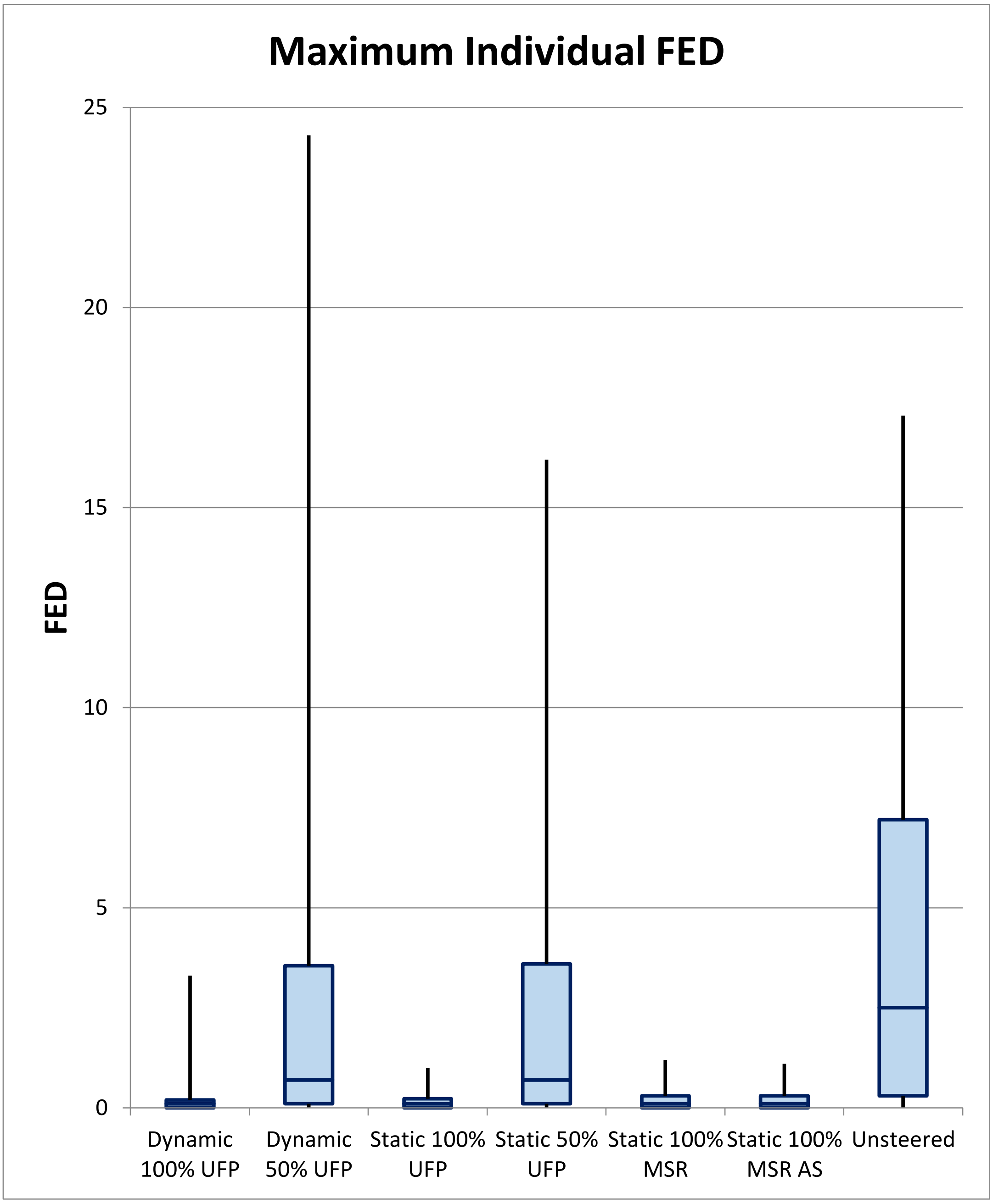

Figure 4-5 - Maximum Individual FED

Fires located on the ground and 1st floor proved far more hazardous than those on the 2nd floor. Once again this was as expected as the hazard is less likely to interfere with as many necessary egress routes one on a lower floor. As the population is equally distributed across the floors, at scenario initiation, in the majority of circumstances fewer occupants will be required to be in close proximity to a hazard based on a higher floor. This is shown by most test types returning higher FED results with lower hazard floor location. The exceptions to this are both dynamic tests and both alarm activated (AA) tests. A possible explanation for dynamic tests giving a higher Total FED rating for the 1st floor than ground floor is due to the particular building layout. All of those evacuating from the second floor are forced through a certain part of the building which could be compromised by smoke. This is demonstrated in Figure 4-6.

Figure 4-6 also depicts CRISP compartments being shown with a variety of shades/colours. These represent different CRISP tenability levels, between 0 and 5 (increased number showing greater hazard), with the darker colours corresponding to higher numbers (less tenable). In this diagram, the room of fire origin has the darkest colour with the highest tenability level. Within the CRISP model, occupants can carry out the "escape" action through rooms that have a tenability level up to and including 4, which means they will evacuate through all but the most hazardous compartments. Occupants here can be seen evacuating through 2 compartments (corridor sections) that have a non-zero tenability level.

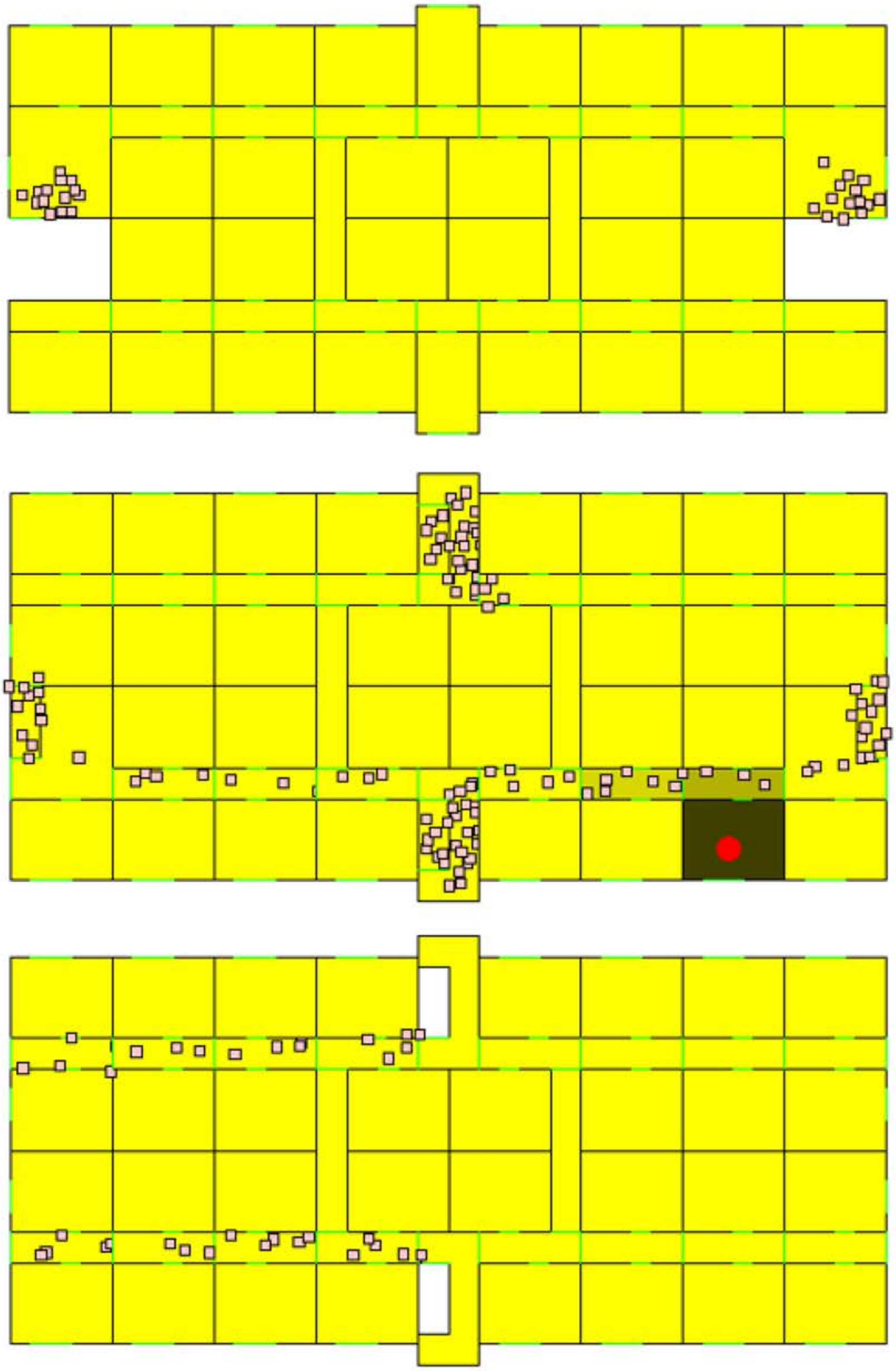

Figure 4-6 - Un-steered evacuation showing how occupants that were originally located on the 2nd floor must use at least part of the corridor containing hazardous conditions to complete evacuation.

Total evacuation time is often used as a measure for evacuation safety [40] so it was necessary to compare egress times for all test types. Both total time and time for 50% of the population to evacuate, were considered. Trends related to time are shown in Figure 4-7 to Figure 4-10.

For an average of total evacuation time across all scenarios the test type with the fastest evacuations was AA 100%, followed by AA 50%. Totally un-steered evacuations were only slower on average than Static 50% UFP and crucially faster than all steered tests with 100% obedience other than Static 100% UFP which has an equal average total evacuation time. When contrasted with FED results, the fact that un-steered tests proved generally faster than steered tests, especially dynamic 100% UFP which was the slowest overall, shows that for this case, total evacuation time is not the most important factor to consider.

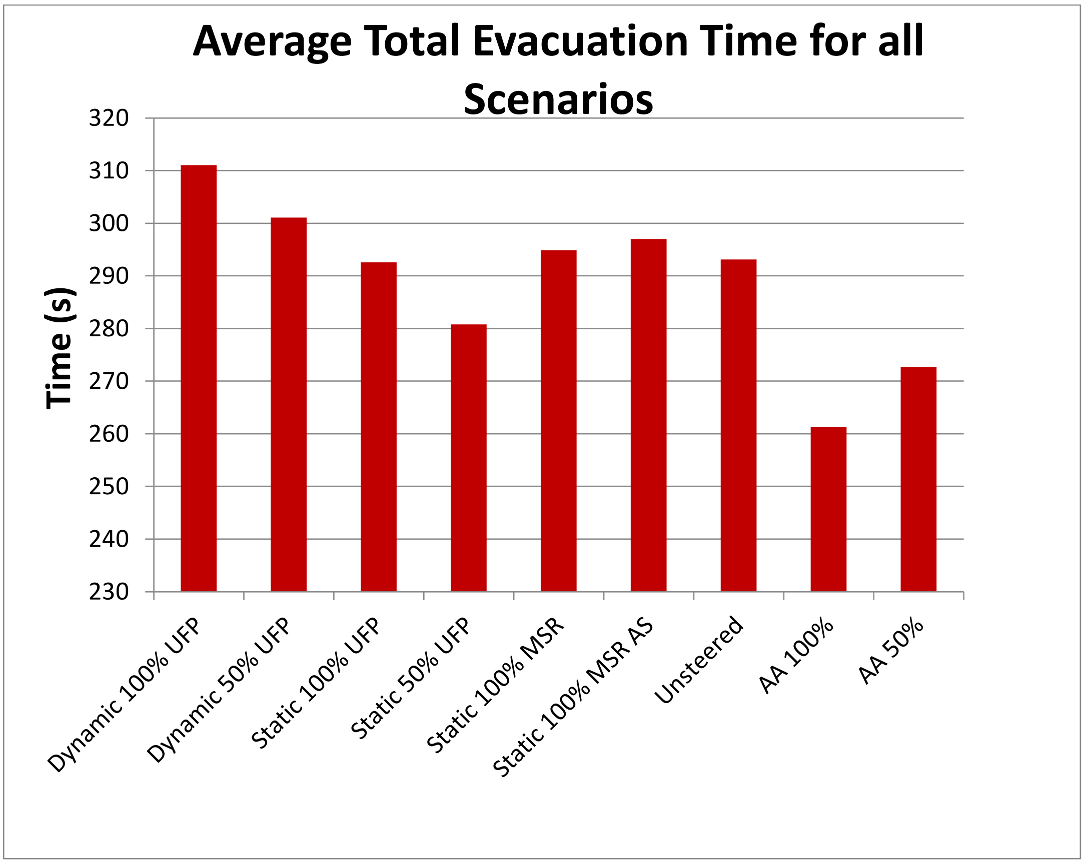

Figure 4-7 - Average Total Evacuation Time for all Scenarios

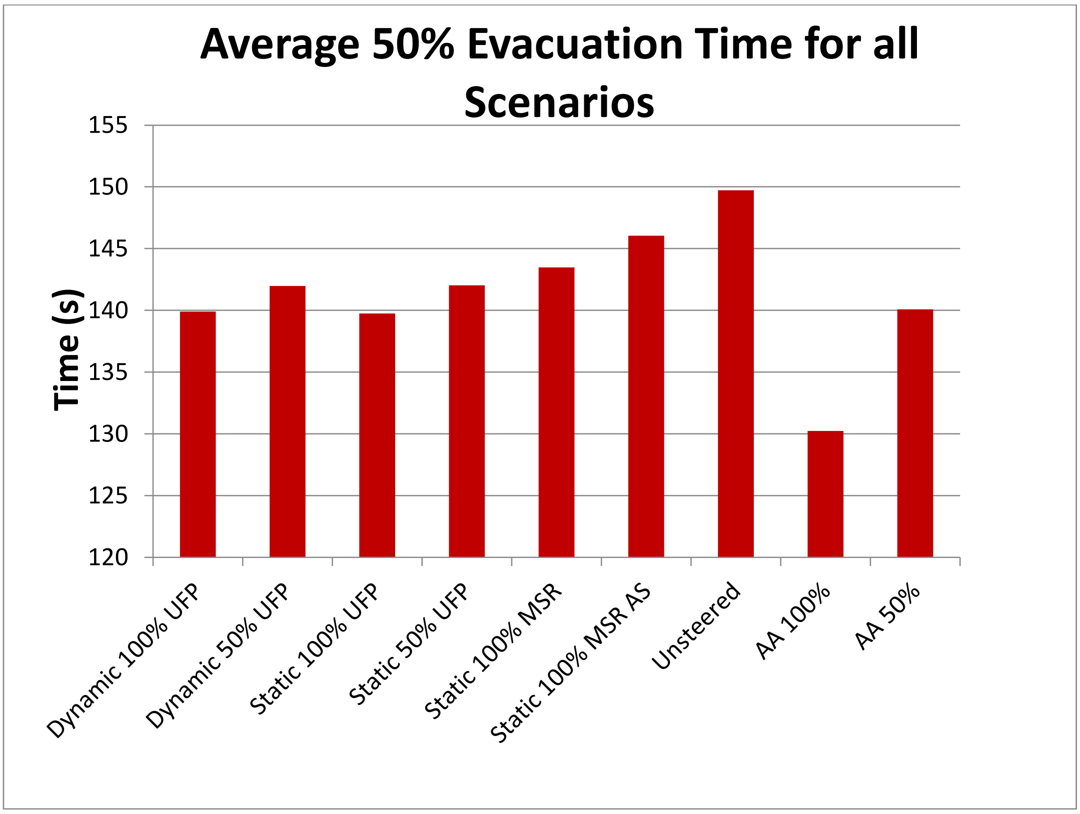

Figure 4-8 - Average 50% Evacuation Time for all Scenarios

Average times for 50% of occupants to complete egress give a slightly different picture. Other than the two AA test types the results more closely match total average total FED, with totally un-steered tests giving the longest 50% evacuation times. Otherwise, the lowest 50% evacuation times are Dynamic 100% UFP and Static UFP with very similar times which also have the lowest 2 total FED results. From these results it is possible to conclude that for this building scenario, time for 50% of occupants to evacuate might more significant to the overall evacuation safety than total evacuation time. This is possibly due to the fact that, at the point 50% of the occupancy have successfully evacuated, the remaining population will also be well on the way to completing egress. It must be noted however, that the differences between 50% evacuation times for each test time are relatively small, with most differences being less than 10%. One possible reason for dynamic tests with 100% obedience resulting in the slowest evacuations is that after a certain point in the simulation, in many instances, all occupants from the 2nd floor will be restricted to one stairwell from each floor to the lower one. This will not occur in many static tests when both stairwells are initially available. Un-steered and disobedient occupants will continue using a stairwell after the DRPS would otherwise have directed them away. This restriction to one set of stairwells will have created a queue which will have resulted in slower evacuations, albeit with lower FED values.

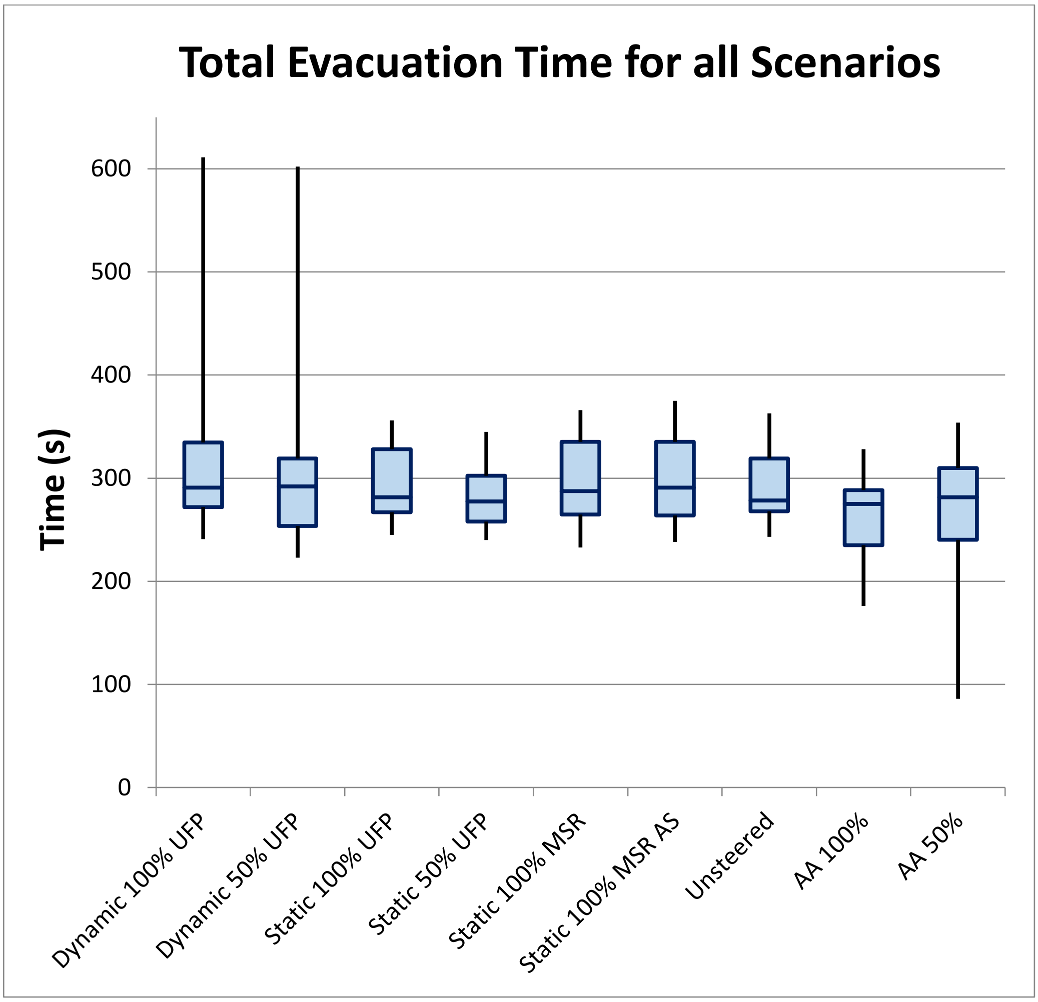

Figure 4-9 - Total Evacuation Time for all Scenarios

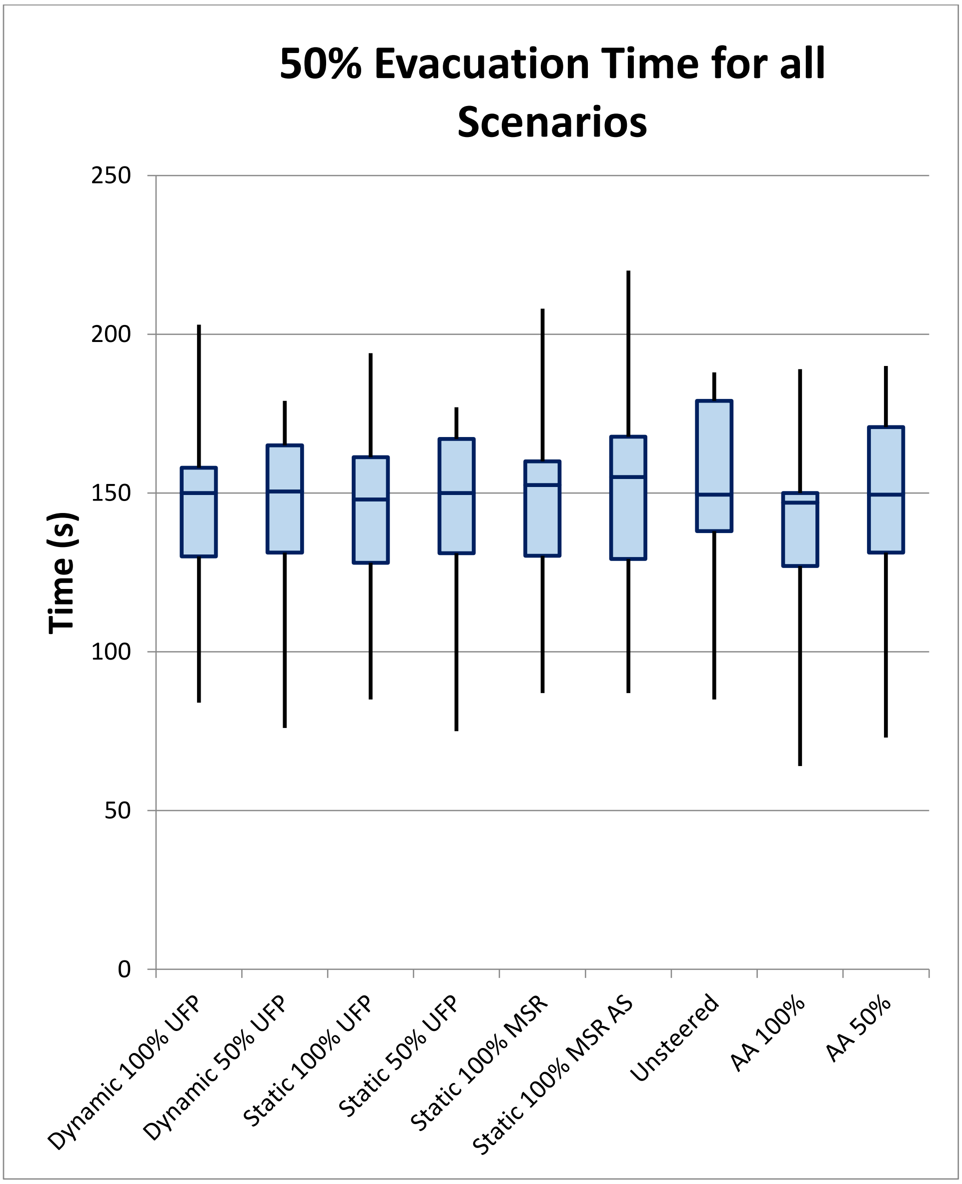

Figure 4-10 - 50% Evacuation Time for all Scenarios

In general all un-steered tests (including totally un-steered and alarm activated (AA) evacuations) give significantly higher FED results, both total and individual, than all steered tests. The exception to this is for corridor based sofa fires, in which the AA 100% obedience test gives the lowest FED results of all and by a substantial margin. A possible explanation for this is that corridor based fires will be detected after a shorter period of time than room based fires, and of these sofa fires will have the slower growth rate. As AA 100% tests resulted in the fastest total evacuation times, and this type of fire will result in fast detection and slow hazard growth it is possible that a large number of occupants will have made it to safer locations by the time crucial stairwells will have become compromised. In this case, simply minimising evacuation time appears to be a more important factor than route choice. Another possible explanation for this is that occupants are permitted to choose windows on the 1st floor, where all corridor based sofa fires were originated, to exit the building. If the degree of difficulty in the room they are in reaches a high enough level, occupants will rightfully chose the window whereas during steered evacuations, the DRPS doesn't consider the windows as a means of escape

Throughout steered evacuations with 100% obedience the only way an occupant could be in the room with such a sofa fire is if their original location was that exact room. However, this is likely to result in alternative paths becoming congested by the comparatively higher occupant load and the subsequent bottleneck may eventually be reached by hazardous smoke, giving the higher FED result. Totally un-steered tests will also include the use of windows but occupants are less likely to enter the room of hazard origin because their action is not immediately set to escape. It can be concluded that, with the exception of one scenario, AA 100% tests failed to produce consistently safe evacuations unlike in simpler scenarios as per the single floor scenario investigated in chapter 3, due to the lower FED values given in totally un-steered and AA 50% tests.

The difference in AA results between Christmas tree and sofa corridor based fires is most likely down to the difference in fire growth rate. It is possible that occupants entered the room of fire origin at an early stage in the simulation, due to the lower time to detection afforded by corridor fires, while it was at a less dangerous tenability level. The speed of fire growth made the compartment become more hazardous while they were already there resulting in high possible exposure.

The results for room based fires were as expected, with dynamic steering producing lower total FED than static steering which in turn gave safer evacuations than un-steered tests. However in the overall results these were dominated by the discrepancies in corridor based fires as they produced comparatively greater total FED values. Smoke is likely not to spread so quickly through the building when the fire is located within a room especially if the only access door is closed. Due to this, slower smoke propagation however it is also likely that alarm detection times will be higher for room fires than corridor based fires, which will have allowed the fire to grow for a longer period of time before detection.

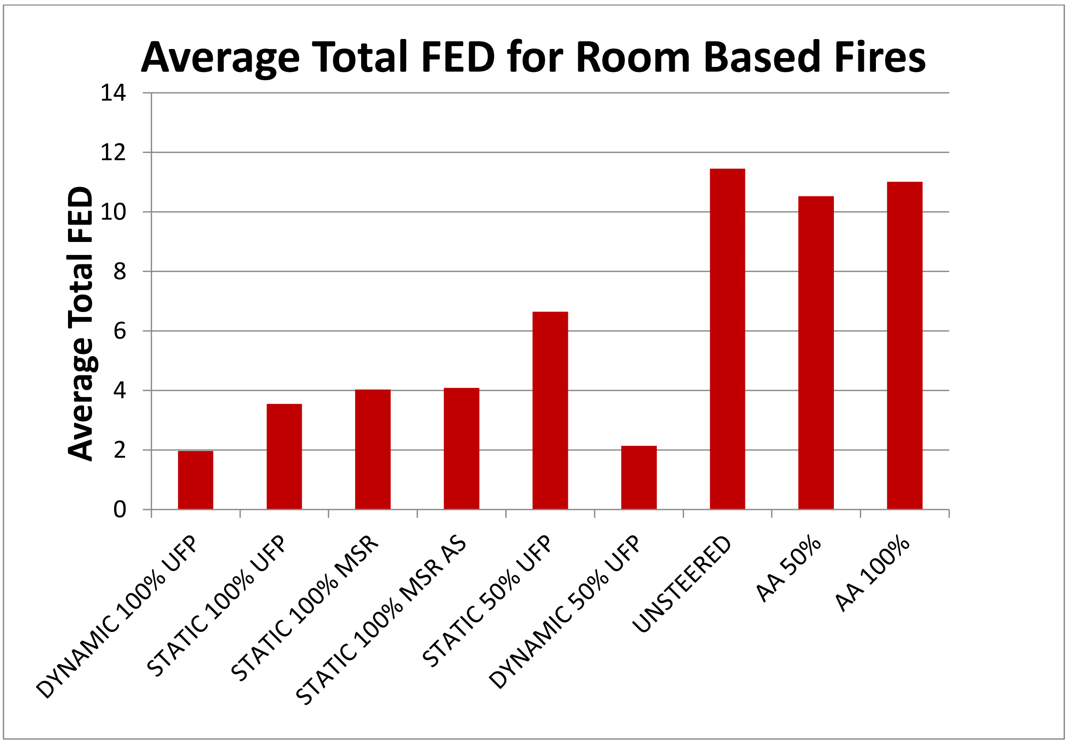

Figure 4-11 - Average Total FED for Room Based Fires

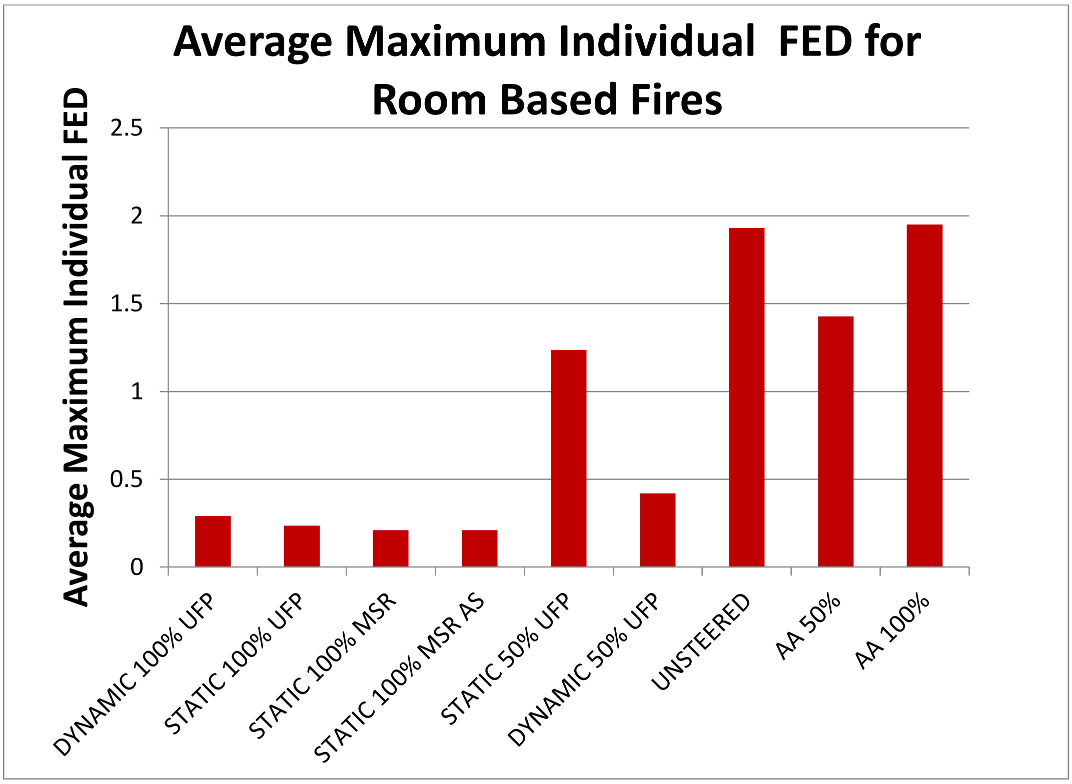

Figure 4-12 - Average Maximum Individual FED for Room Based Fires

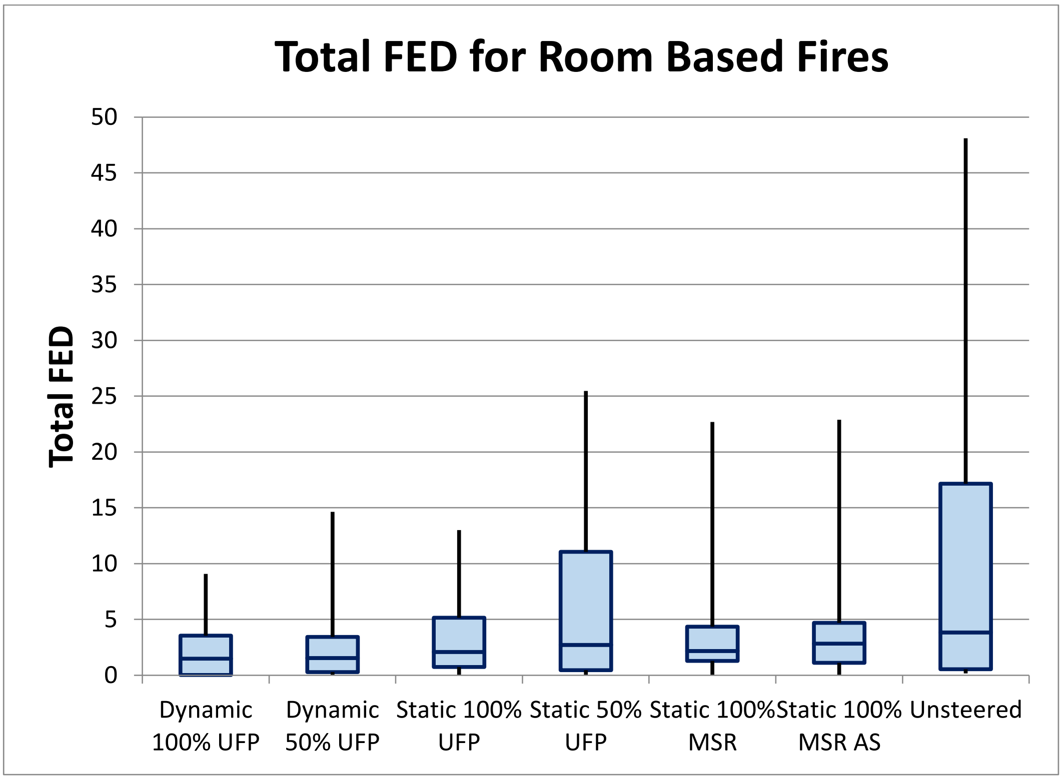

Figure 4-13 - Total FED for Room Based Fires

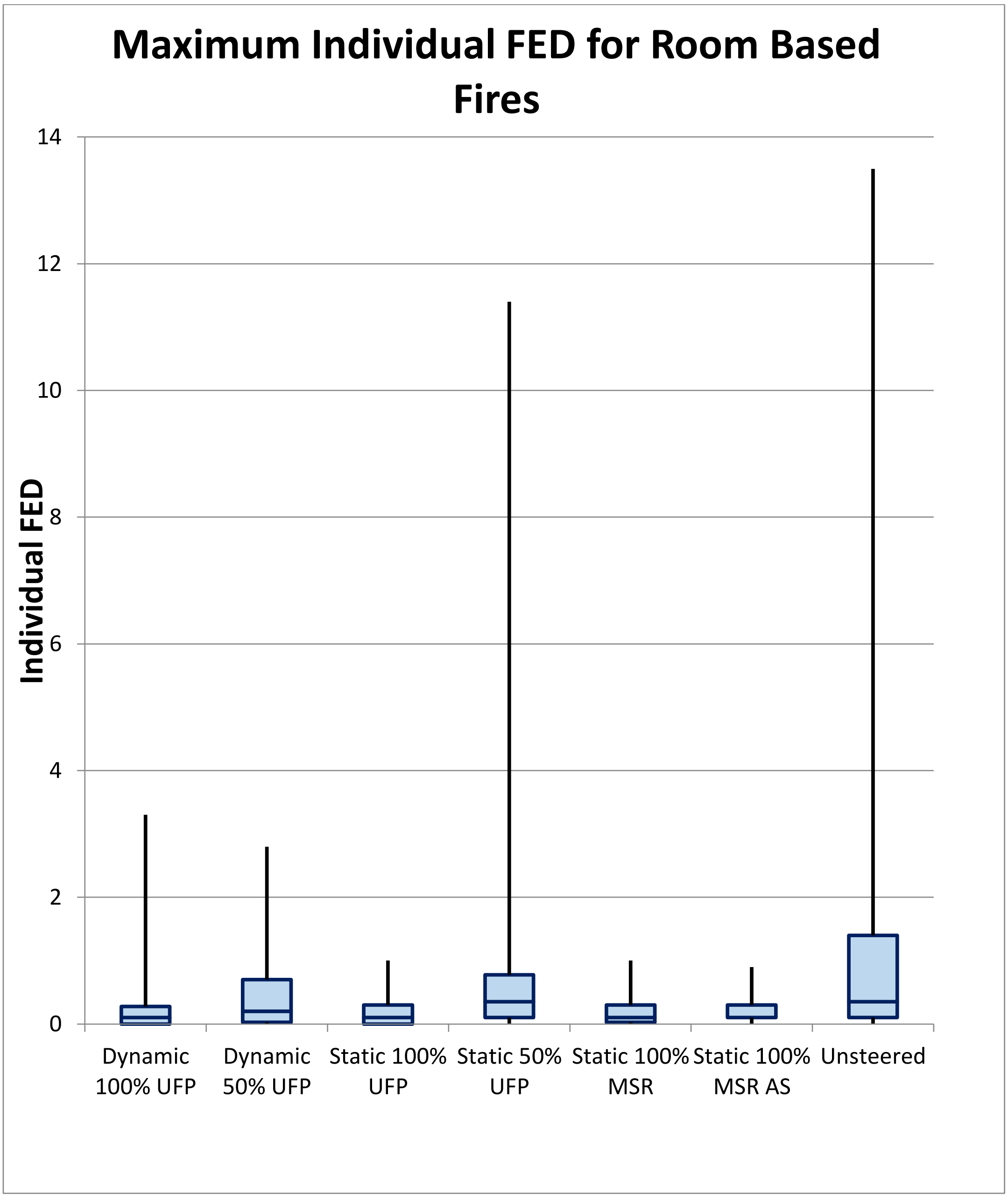

Figure 4-14 - Maximum Individual FED for Room Based Fires

As can be seen in Table 4-1; when comparing Total FED results for all scenarios the Dynamic 100% UFP results compare favourably with all static steering results. The only scenarios where the discrepancies are small or irrelevant are when the hazard is situated on the second floor and when the initial burning object is a corridor based

Christmas tree. The similarity on the second floor is irrelevant as the results for all 100% obedience steered evacuations shows that there is relatively little hazard exposure. This is confirmed by the Maximum individual FED ratings shown in Table 4-2 giving a value of 0 for all second floor based fire scenarios with 100% occupant obedience. The relatively fast growth, peak and decay of the Christmas tree fires is likely to account for the similar results for these fire types as the major advantage of the dynamic system is when smoke progresses through a building to interfere with what was originally the fastest, safest escape route chosen by the static system upon initiation. With the faster growth and decay fire, however the egress routes will become affected at an earlier stage in the evacuation but will not deteriorate to the same extent as for slower growth, sofa based fires. Corridor based sofa fires which were likely to produce a more hazardous environment give a larger discrepancy between static and dynamic steered tests. An example of why the dynamic system has produced better overall results is demonstrated in the following series of diagrams.

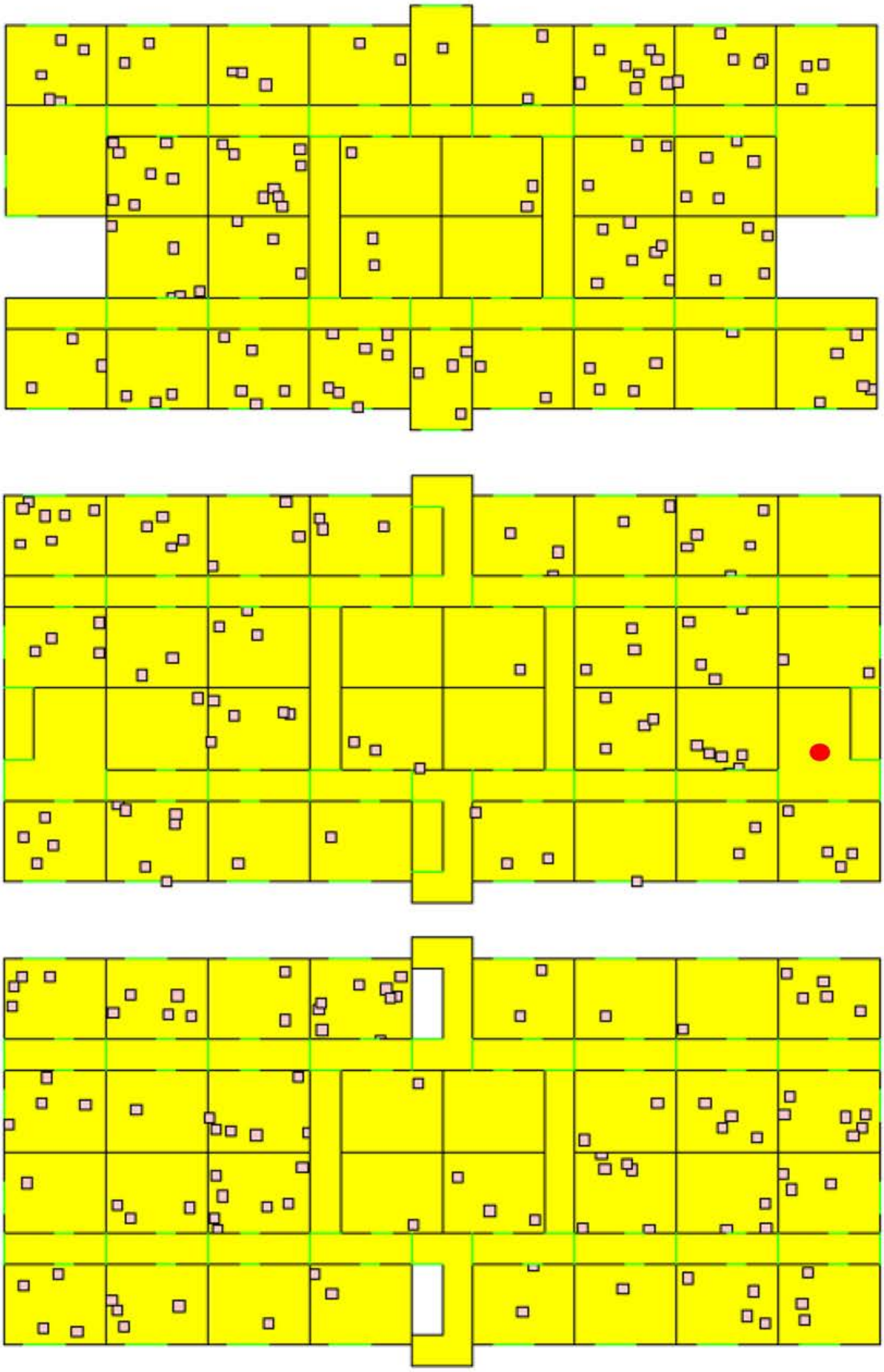

Figure 4-15 - Test at Initiation (Note fire location in room 69)

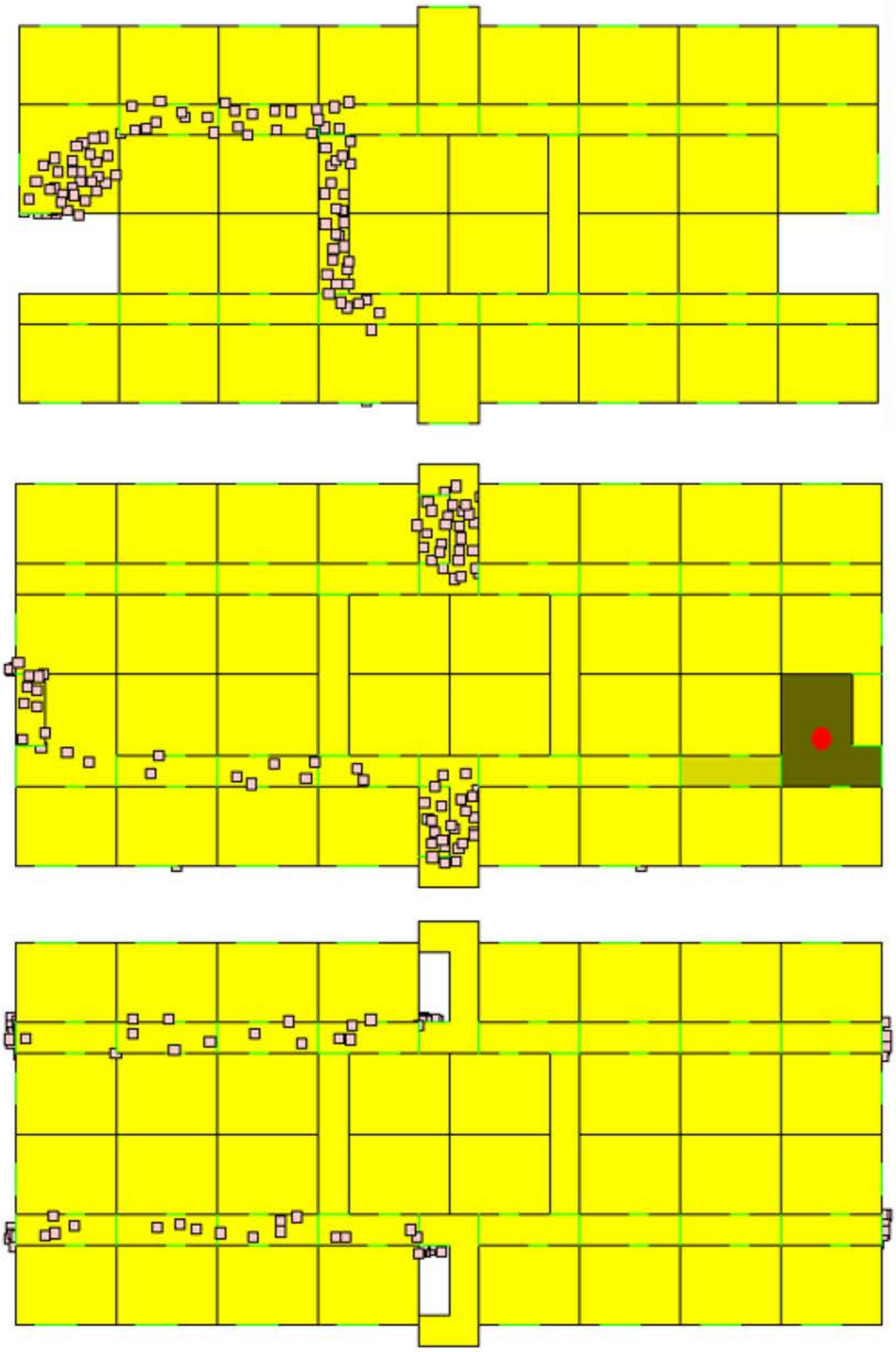

Figure 4-16 - 125 seconds. Occupants are still being instructed to use the nearer stairwell when descending from the 1st to ground floor.

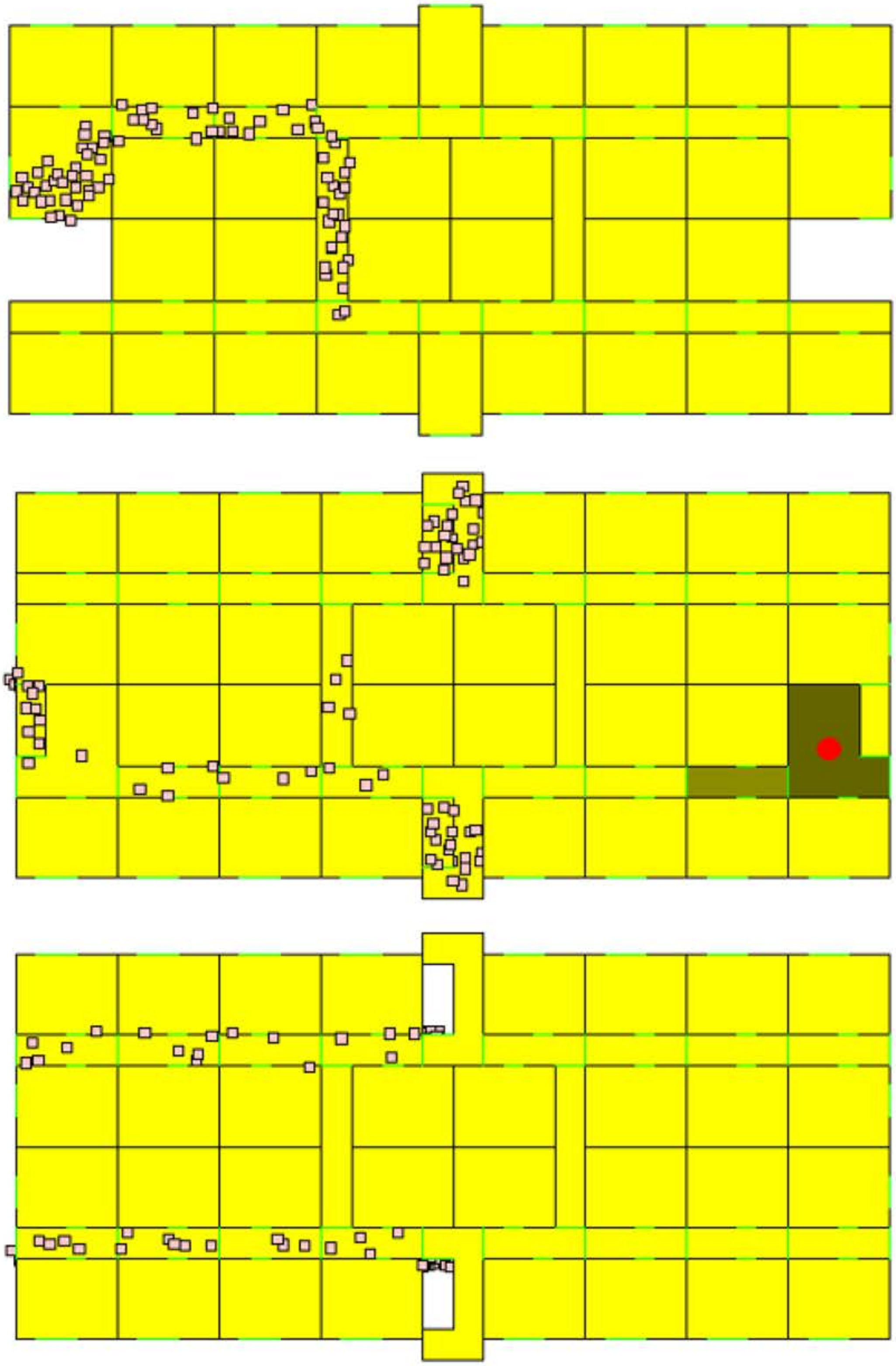

Figure 4-17 - 130 seconds. Occupant direction on 1st floor has changed as they are directed towards the alternative stairwell as sensor data has indicated that utilising the nearer stairwell will have an increased hazard cost.

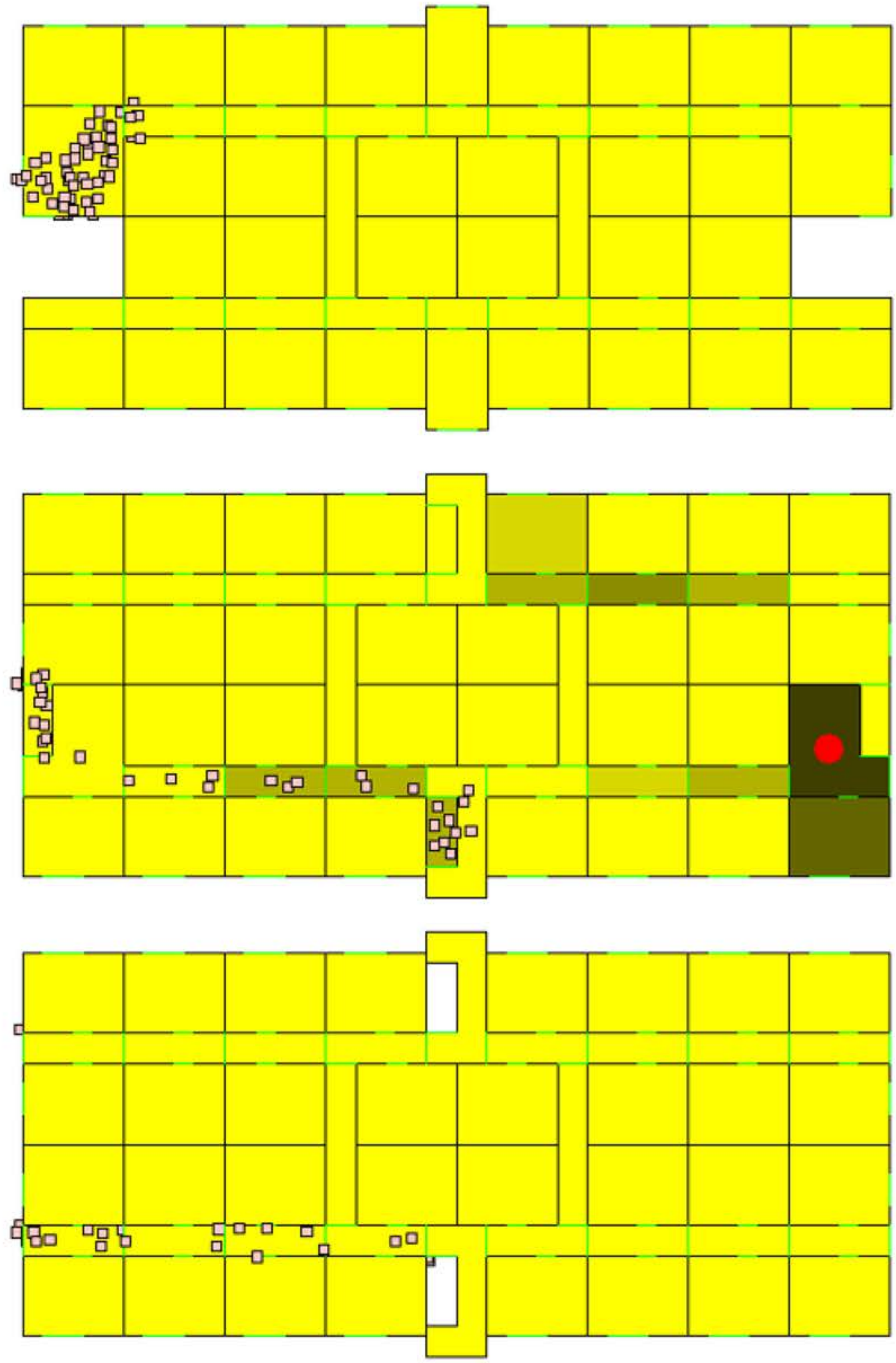

Figure 4-18 - Static Steered Test of identical scenario at 180 seconds. Note that the occupants on the 1st floor are still utilising the nearest stairwell despite being compromised by smoke. Sensor data had measured an increase in temperature after approximately 130 seconds, as per the previous diagram.

The three different Static 100% tests resulted in similar overall FED levels but marginally lower values were given by the UFP tests, in all corridor based sofa fires. This result is unexpected as it was hypothesized that multiple solution runs with or without additional information from a priori occupant monitoring would provide safer evacuation due to the greater knowledge employed and number evacuation solutions evaluated. All corridor based results are presented in Figure 4-19 to Figure 4-26.

The goal of employing multiple solution runs was to try and improve upon UFP tests by reducing overall hazard exposure. This was achieved in corridor based sofa fires with Christmas tree corridor based fires giving higher FED results for MSR tests. As the initial location of the fire is all that is known during static steered tests with corridor based fires (due to zonal alarms being in located in corridors) this result can only be due to the specifics of the building layout and the subtle differences between where sofa based corridor fires and Christmas tree fires are located. As sofa corridor fires are all on the 1st floor they will always eliminate one stairwell from the 1st to 2nd floor, all occupants from the top floor are directed to the same stairwell.

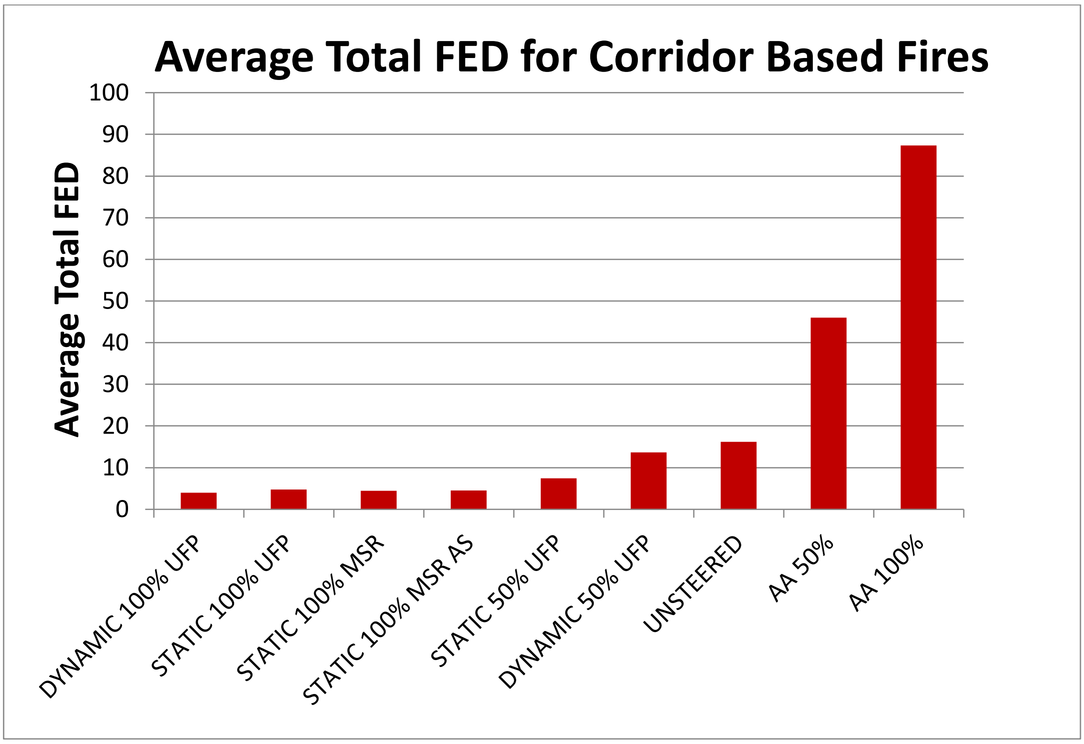

Figure 4-19 - Average Total FED for Corridor Based Fires

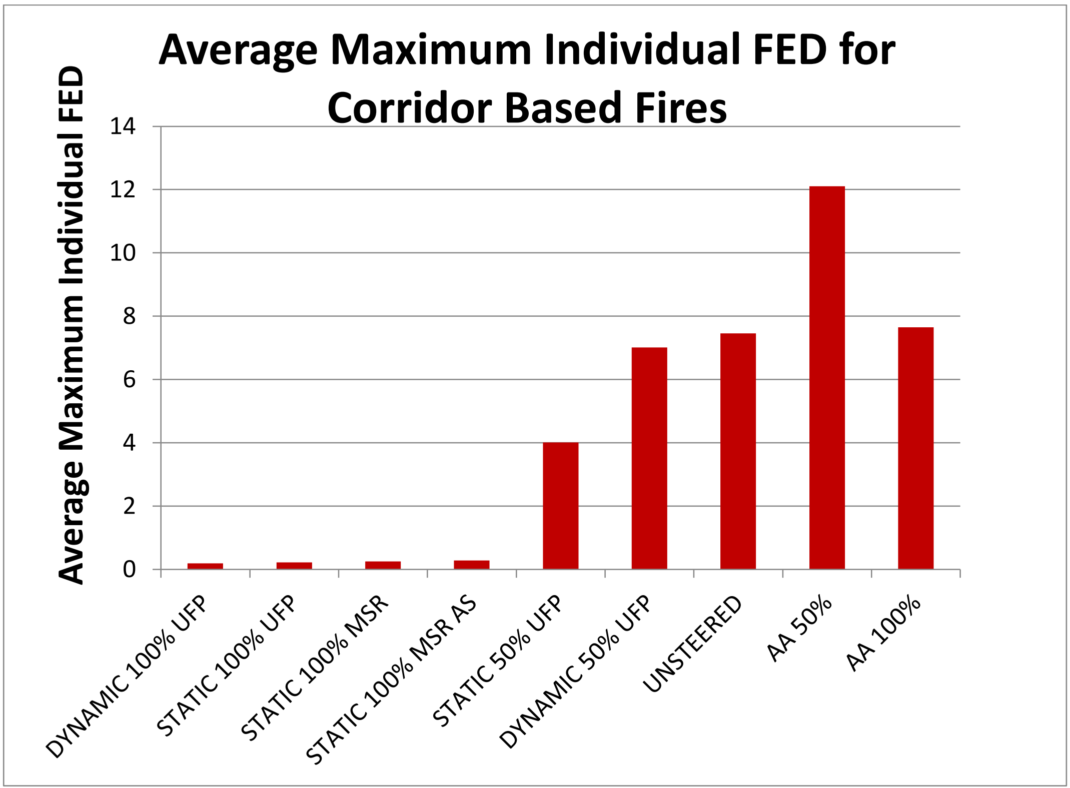

Figure 4-20 - Average Maximum Individual FED for Corridor Based Fires-

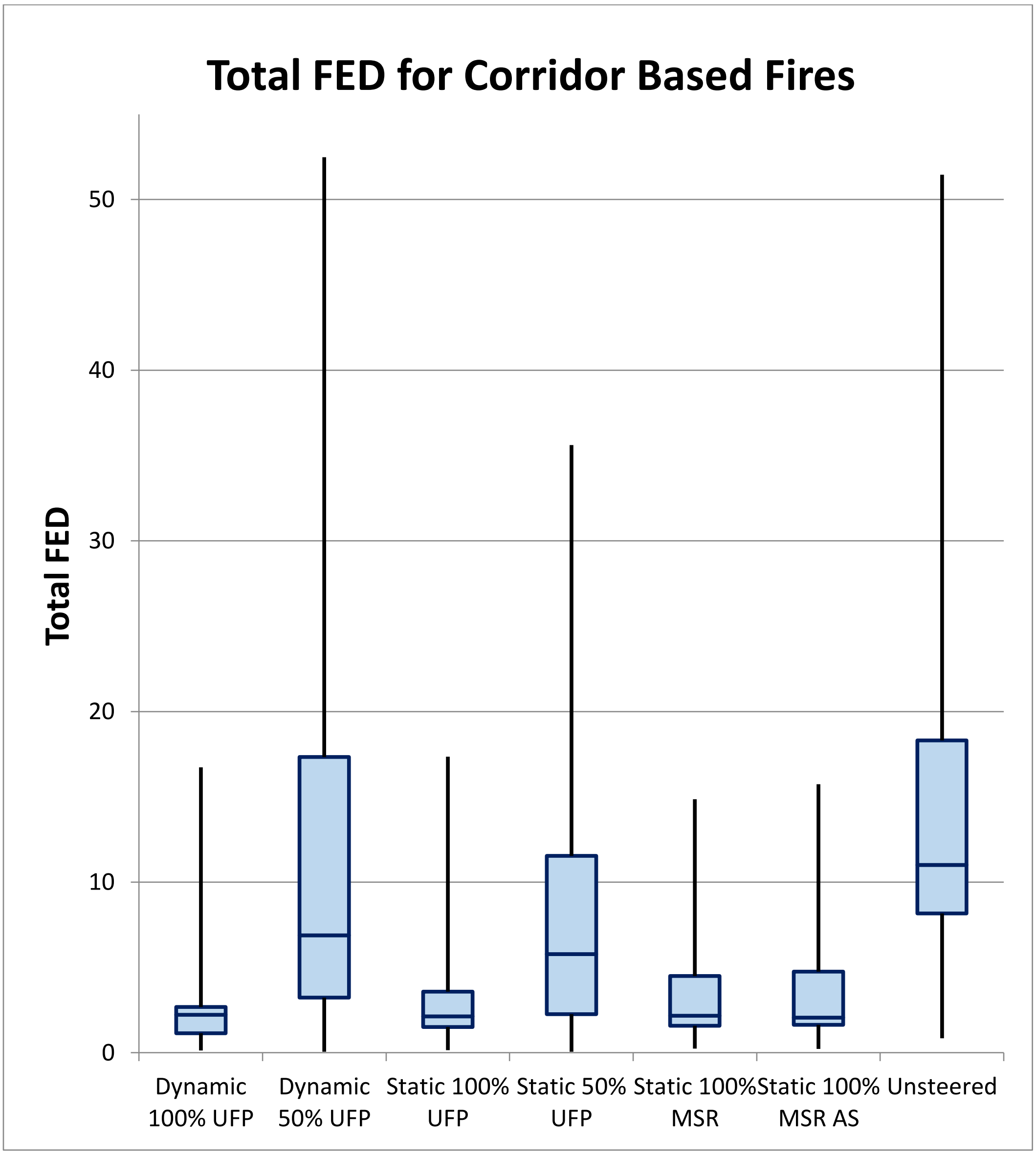

Figure 4-21 - Total FED for Corridor Based Fires

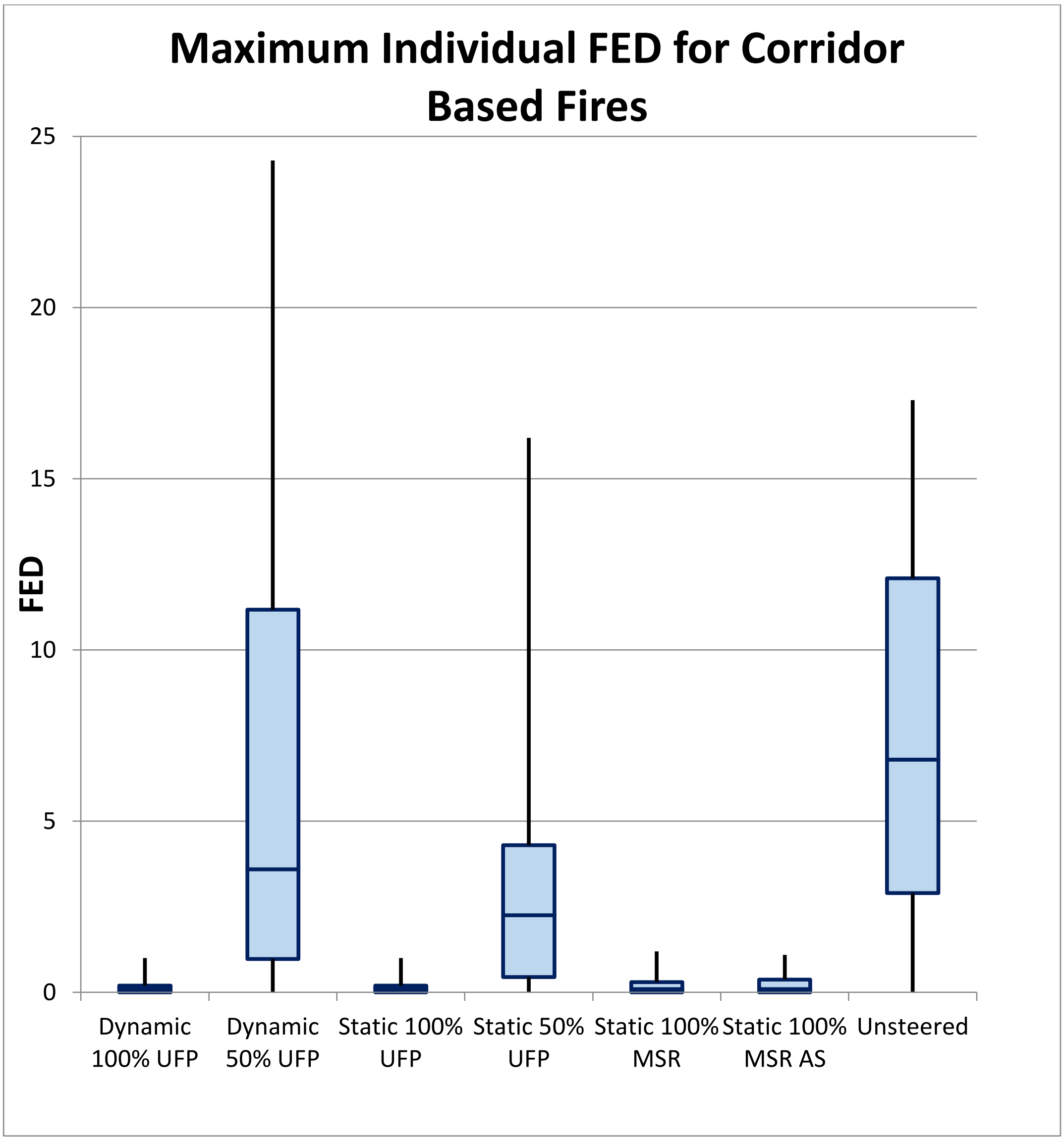

Figure 4-22 - Maximum Individual FED for Corridor Based Fires

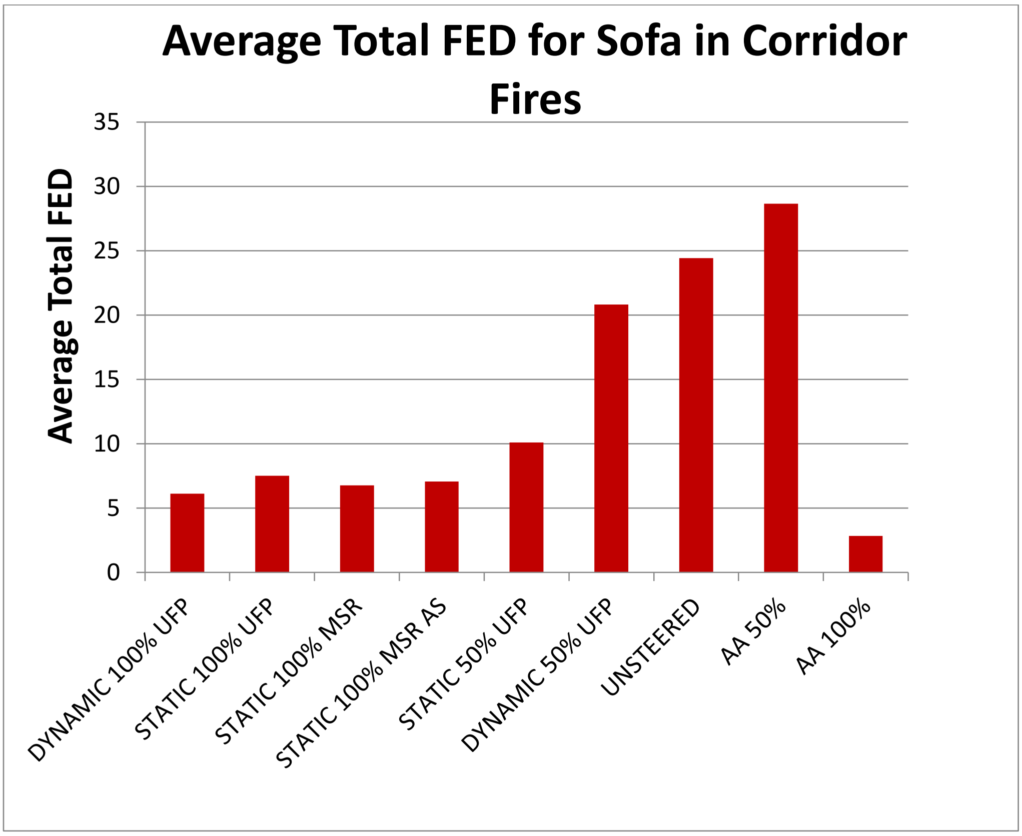

Figure 4-23 - Average Total FED for Sofa in Corridor Fires

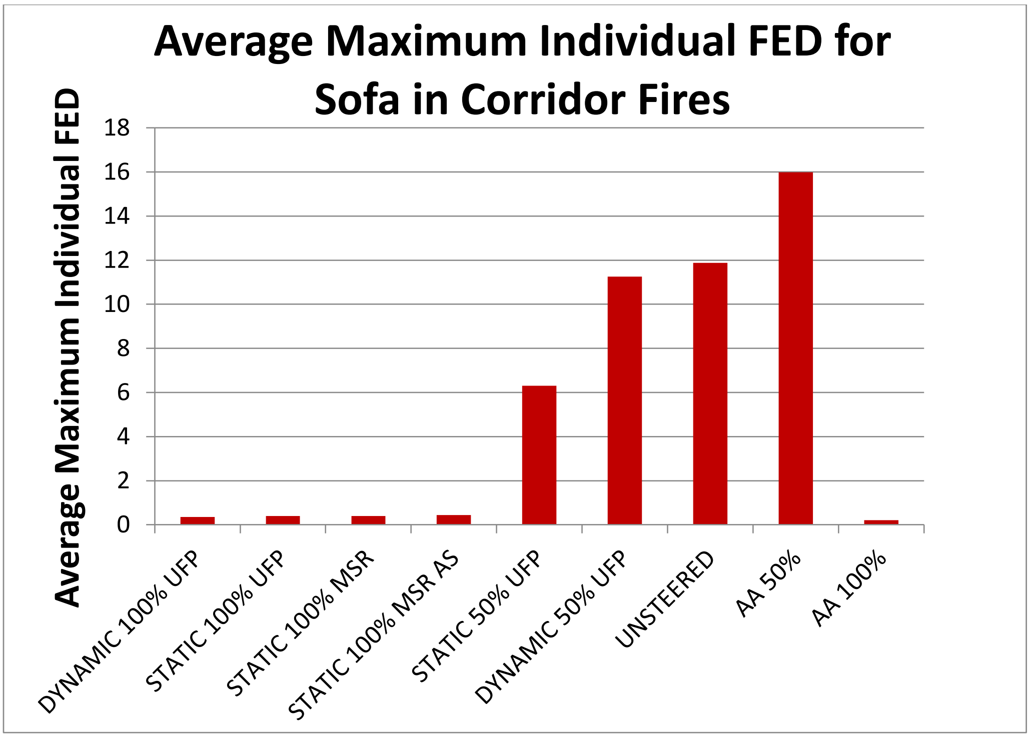

Figure 4-24 - Average Maximum Individual FED for Sofa in Corridor Fires

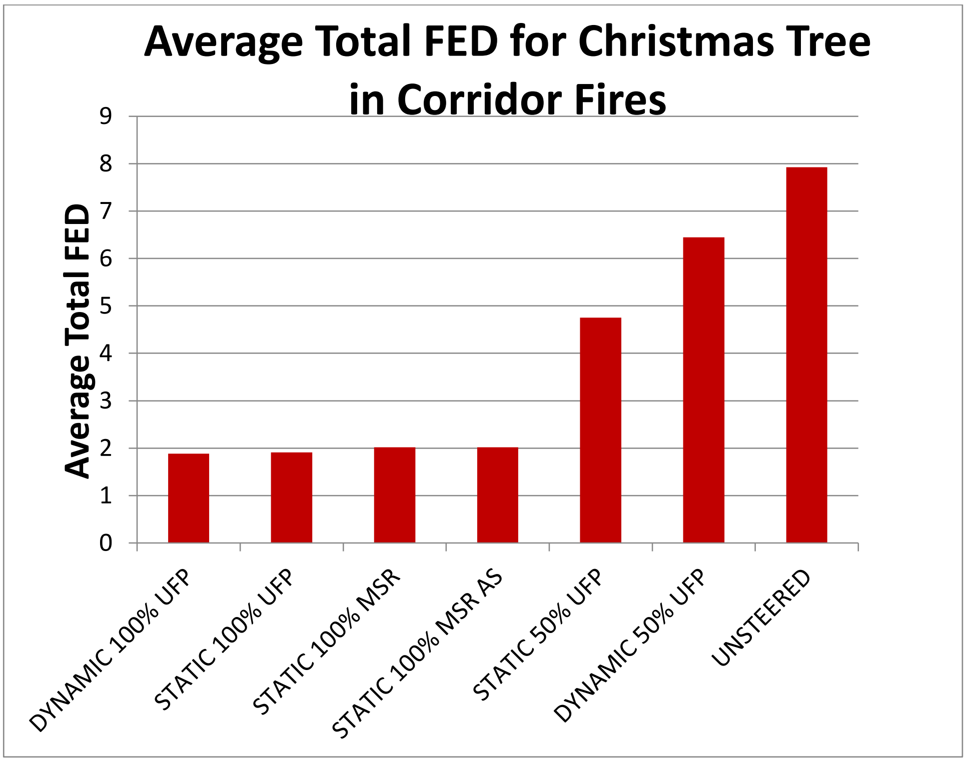

Figure 4-25 - Average Total FED for Christmas tree in Corridor Fires

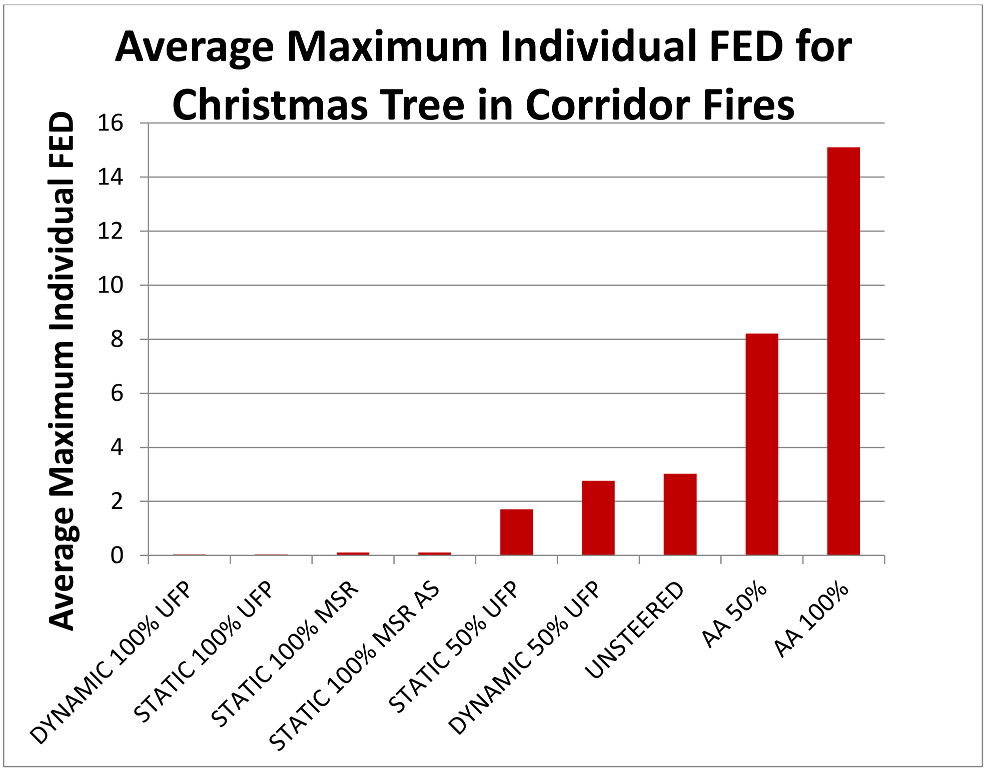

Figure 4-26 - Average Maximum Individual FED for Christmas Tree in Corridor Fires

During static UFP tests all of these occupants will then be instructed to the same stairwell which leads to the ground floor. This high number of occupants using a single stairwell could have resulted in a bottleneck which may have exposed individuals to disseminating smoke at later stage in the simulation. On the contrary, for MSR tests some occupants originally on the second floor will have been directed to the other available stairwell from the 1st to ground floor (which will still be available in this situation due to the building layout), resulting in less queuing and putting more occupants at a greater distance from the hazard at an earlier time in the evacuation. Further evidence for this explanation is that the maximum individual FED values are equal, which would reinforce the argument that a greater number of occupants were exposed during UFP tests, although without individual danger being higher. This positive result for MSR tests compared to UFP tests is not repeated for Christmas tree fires on the 1st floor, and the most likely reason is that they did not immediately eliminate a stairwell from the 1st to 2nd floor, but instead from the 1st to ground floor. In such a case there is no advantage to be gained from splitting traffic between stairwells because only one is available leading away from the floor of hazard origin, where the majority of occupant hazard exposure will be experienced.

A possible explanation for the general trend for the remaining scenarios for static 100% test types to favour UFP tests is that they simply involved a lower evacuation times. Static 100% UFP tests had both a lower 50% evacuation and total evacuation time than either MSR test, across nearly all statistical measurements. For ground floor fires in particular, where certain initial fires may have resulted in several originally available egress paths being affected, overall evacuation time may have been more important than original path choice.

The two Static 100% tests involving multiple solutions runs produced similar results but that with *a priori* occupant movement knowledge produced consistently higher total and maximum individual FED than those without. This is an unexpected result, as the greater knowledge of occupant movement throughout the building was predicted to produce more accurate movement predictions, and thus safer evacuations. The tests with adjusted node speed and working area also produced overall slower evacuations. From these arguments it can be concluded that this increase in system sophistication may not be beneficial for a scenario of this particular level of complexity.

The difference between 100% and 50% obedience levels for both static and dynamic tests is substantial for all scenarios with the exception being for dynamic steered tests during room based fires, in which case it produced lower total FED values than all static and un-steered tests. However, even in this case the maximum individual FED remains significantly higher for 50% obedience than any 100% obedience, steered test. Static 50% obedience results are consistently worse than all static 100% obedience tests, which was the expected outcome. Both 50% obedience steered tests do however produce safer overall evacuations than un-steered tests which is a positive result in terms of demonstrating the potential benefits of the system.

What is unexpected is how dynamic 50% FED values are overall higher than those for static 50% tests. All corridor based fire scenarios result in higher dynamic 50% FED values than static 50% values, the biggest discrepancies being for sofa fires where the dynamic FED average is more than double that for static. When comparing the spread of maximum individual FED results across all scenarios, it is clear that there are a relatively small number of dynamic 50% tests that result in occupants suffering a far higher than average dose, with there being very little difference in the quartile values. A possible, simple explanation for this unexpected overall FED result is that a few individual occupants in dynamic 50% tests received a much greater dose than in other test types. The fact that the maximum individual FED recorded was higher in dynamic 50% tests than totally un-steered tests is further evidence for this.

When comparing the results of this chapter, with those for the single floor scenario discussed in chapter 3, there are a number of key differences. Firstly it should be noted that comparing totally un-steered results isn't useful because of the different CRISP human behavioural rules used between the two scenarios. In chapter 3 these tests produced the consistently least safe evacuations whereas in this chapter that accolade goes to the AA tests. Due to the likelihood of an intelligent system being installed in an office type building, rather than a residential building, the results from this chapter are likely to give the fairer appraisal. This change in behavioural rules will also have affected how disobedient occupants will have responded to the event. As un-steered or disobedient occupants are less likely to follow actions such as investigating fire and rescuing others, which at the population densities involved, would have resulted in far more congestion and generally longer evacuations it can be concluded that this chapter will have provided are more challenging environment for the DRPS to improve evacuation safety.

The comparative failure of AA tests to result in safe evacuations can most likely be attributed to a substantial increase in hazard level and the lack of direct initial line of sight to the hazard for a large proportion of the occupants. This will have caused occupants to have entered stairwells directly above a hazard on the lower floor oblivious to the danger resulting in a large hazard exposure. It is fast growing corridor based fires (Christmas tree) where this is most apparent.

Possibly the most important comparison to make is that dynamic 100% steered tests consistently result in significantly safer evacuations than all static tests, which was not the case in chapter 3 where the results were objectively equal. It was expected that increasing the building complexity would increase the impact of increasing DRPS sophistication and in this case that has proven true. An example of why this is the case was demonstrated by Figure 4-15 to Figure 4-18. Obedience, although investigated in less detail in this chapter, was shown to have a similar effect, despite the changing of CRISP human behavioural settings. Another difference is that, in terms of overall results, static 50% tests result in safer evacuation than dynamic 50% tests, which was not the case in the single floor building layout.

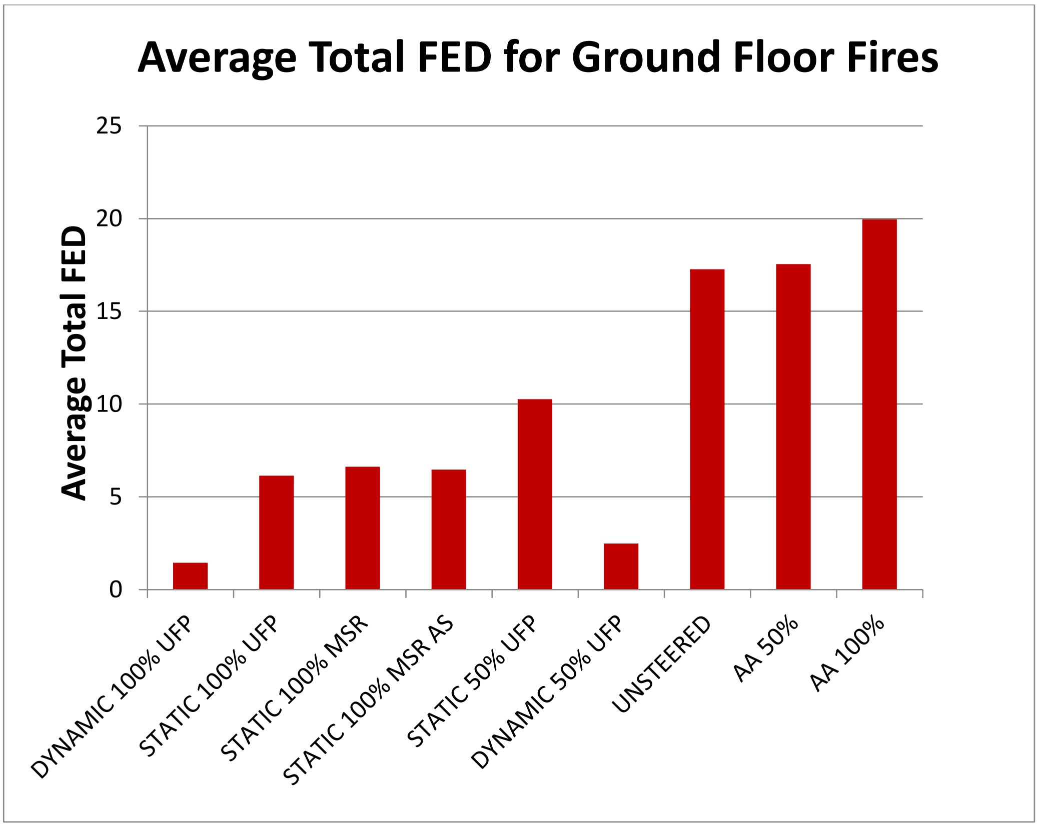

Figure 4-27 - Average Total FED for Ground Floor Fires

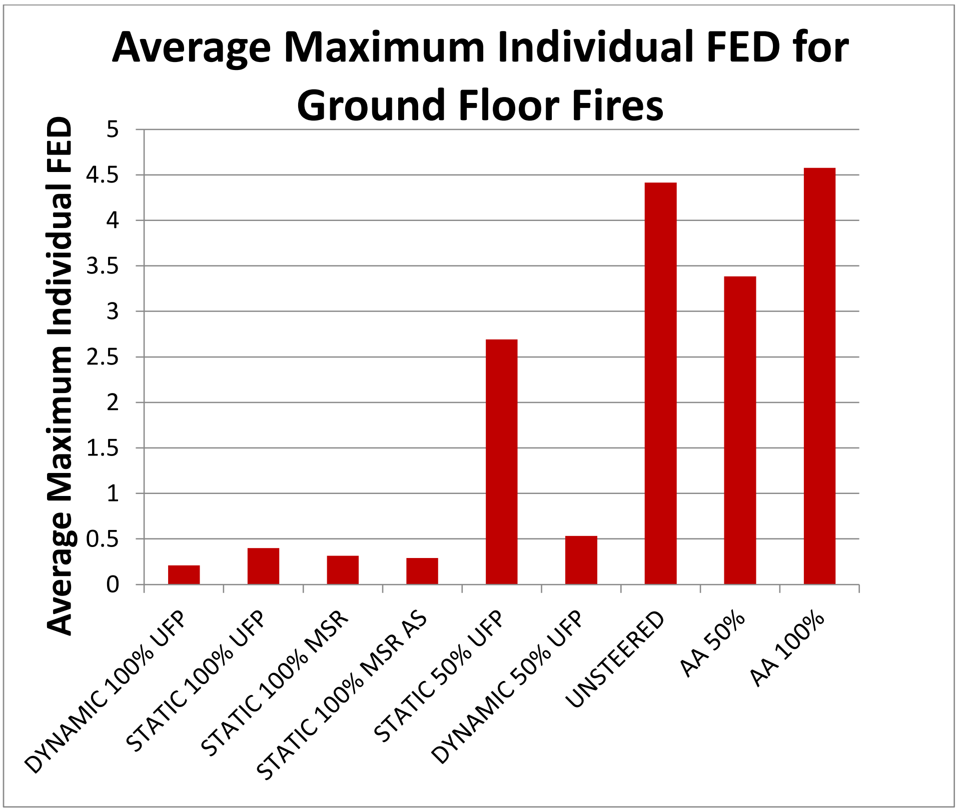

Figure 4-28 - Average Maximum Individual FED for Ground Floor Fires

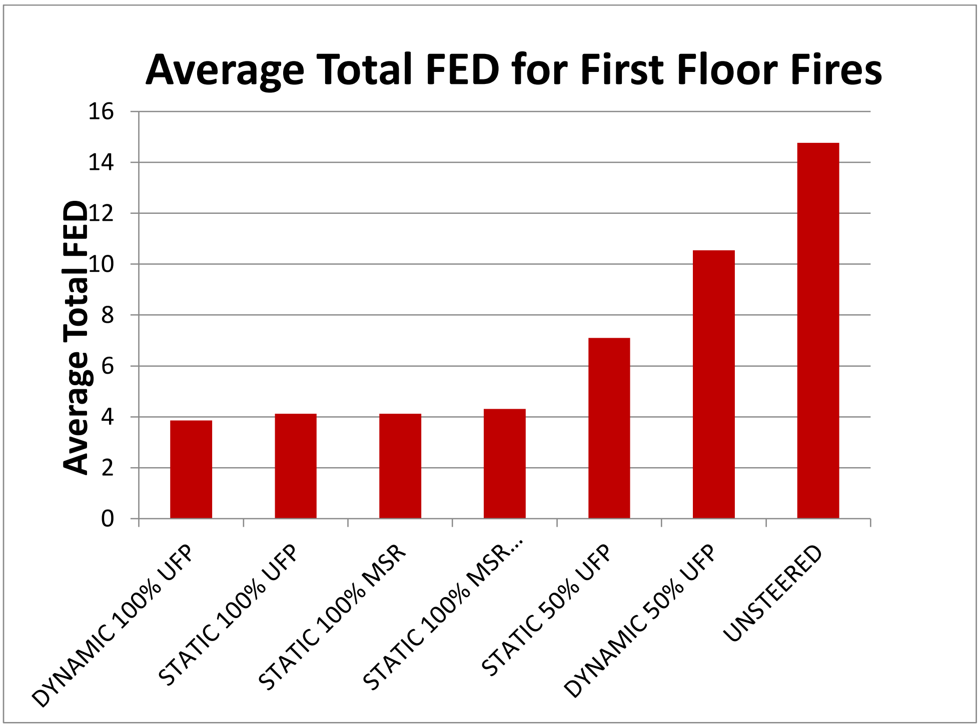

Figure 4-29 - Average Total FED for First Floor Fires

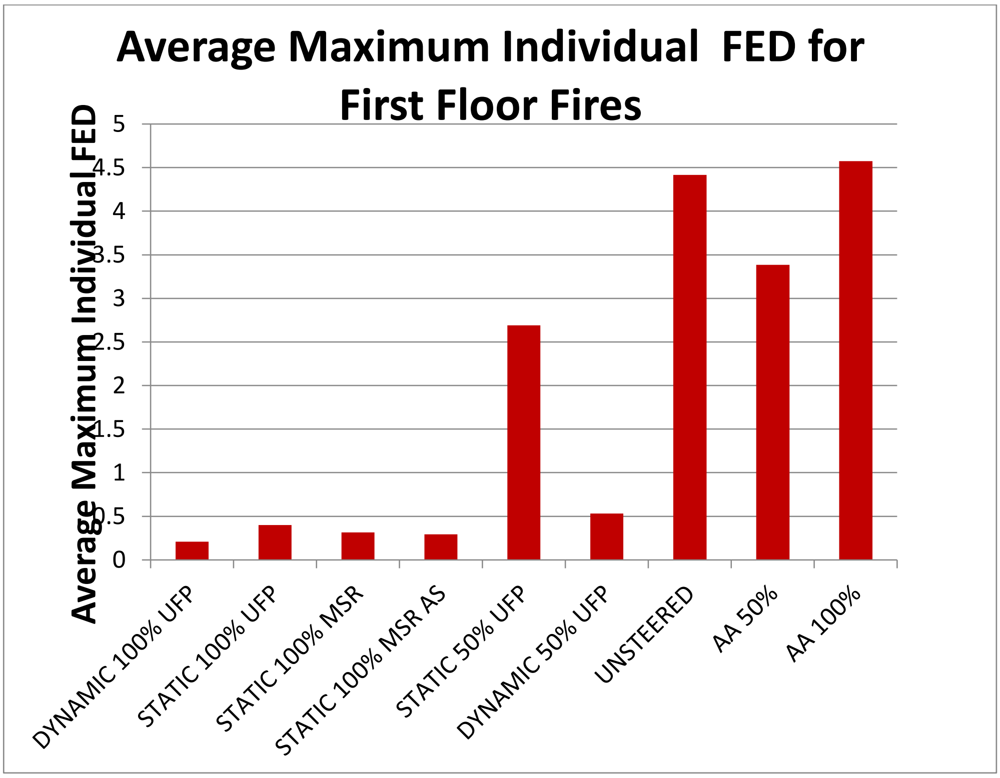

Figure 4-30 - Average Maximum Individual FED for First Floor Fires

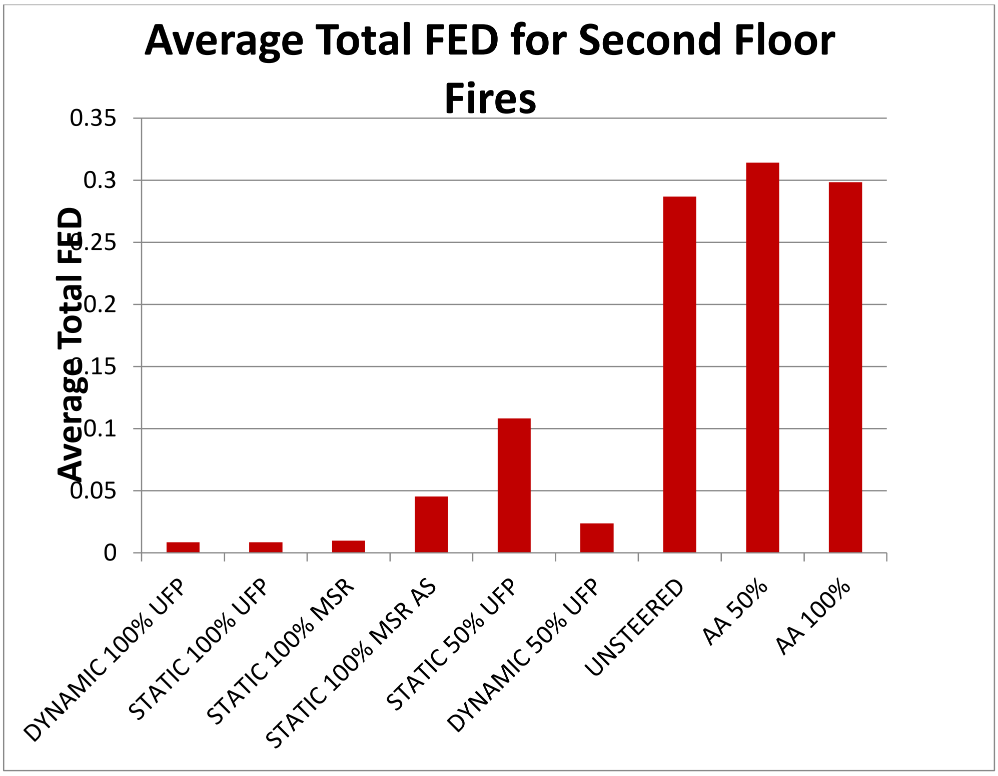

Figure 4-31 - Average Total FED for Second Floor Fires

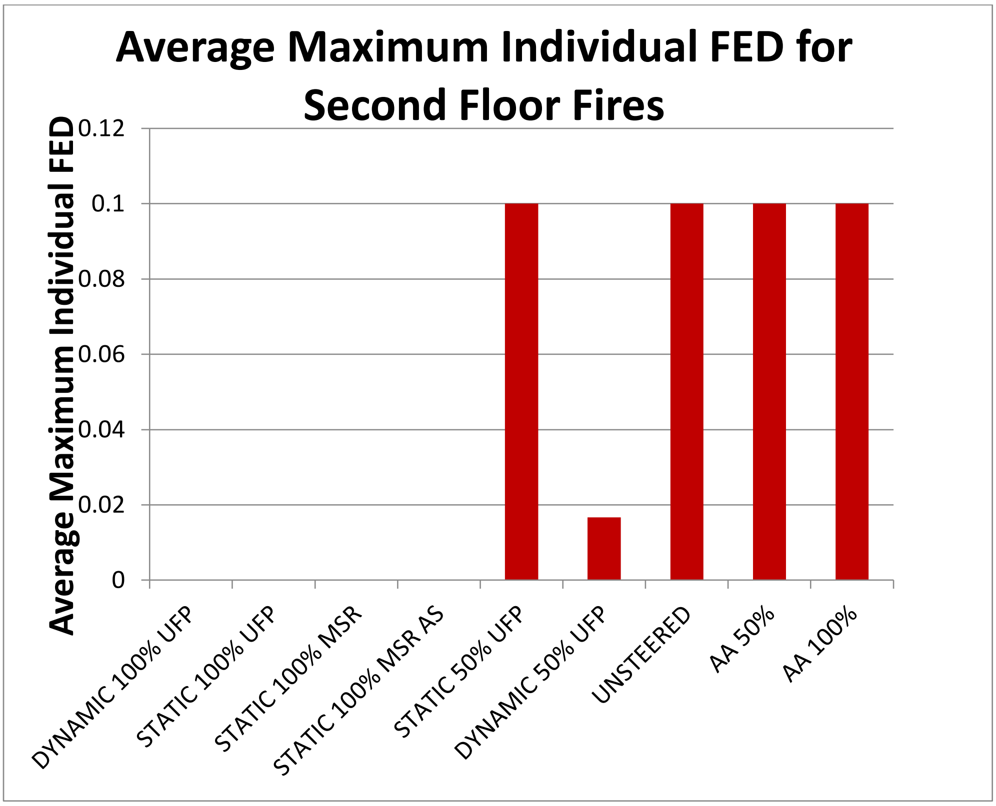

Figure 4-32 - Average Maximum Individual FED for Second Floor Fires

It can be concluded from this chapter that the increase in fire severity, population and building complexity has increased the potential benefit of an intelligent system. The fact that both static and dynamic 50% obedience tests result in safer evacuations than both AA 50% and totally un-steered in every scenario is more significant in demonstrating the benefits of the intelligent system. The scenario (corridor based sofa fires) where AA 100% tests resulted in safer evacuations than all steered tests can be offset by the scale of the opposite trend for all other scenarios. This result assumes that all occupants move towards an exit as soon as they are aware of an alarm which is at best, ambitious.

However it is not such a simple trend in terms of increased DRPS sophistication. Dynamic steering generally outperforming static steering was a good result for the effectiveness of increased sophistication but conversely, increasing the number of evaluated solutions for static tests did not bring any consistent improvement. The use of *a priori* movement knowledge also did not bring any improvement in overall evacuation safety and was possibly even a hindrance in this scenario. As static MSR did improve over static UFP for certain scenarios it is possible to attribute the overall failure to the intricacies of the building, where there were relatively few different paths to choose between, from the upper floors. The consistently higher FED values resulting from static MSR AS tests compared to static MSR was a negative result but it has also shown that the implementation of dynamic over static steering is more significant than the number of solutions evaluated, at least for the building layout considered in this chapter.

It should be noted that dynamic tests with multiple evaluated solutions were carried out but it was evident from early testing that this was not an effective steering method for the scenario involved and thus was not fully investigated in this chapter. This was another disappointing result regarding the effectiveness of increased DRPS sophistication but as with the static MSR results, this may be attributable to the specifics of the building layout. It is therefore clear that a further scenario is required to thoroughly test all aspects of the system. The requirements of the further scenario will include the availability of a greater range of possible, significantly different egress paths from upper floors as well as a generally more realistic building layout.

5 Complex Building Scenario

This chapter demonstrates the dynamic route planning system being applied to a more complex building than in previous chapters. The building layout in this chapter is based on the University of Edinburgh building at 50 George Square and therefore provides a more realistic setting for demonstrating the effectiveness of the intelligent system. When implemented within CRISP the building consists of 315 compartments over five floors. As discussed, the building layout used in chapter 4 did not provide enough different evacuation route options from the upper floors due to their only being two stairwells connecting each floor. For example, in the event of a fire on the 1st floor only one stairwell from the 2nd to 1st floor would be considered viable, thus negating the effectiveness of occupant steering using multiple solutions. As the building considered in this chapter has 4 stairwells from each floor to the next, it is hypothesized that the effectiveness of multiple solution runs (MSR) compared to universal fastest paths (UFP) would be greater than in the previous chapter.

5.1 Scenario Description and Test Method

For the sake of ease of implementation within the CRISP model, the building layout was simplified although the exits and stairwells were maintained to provide as accurate a representation as practically possible. The most significant changes were the omission of the basement and the flattening of the floor of each room. Figure 5-5 to Figure 5-1 display floor plan for each floor respectively, as implemented within CRISP and used to obtain the results presented in this chapter. The single lift within the building was also omitted due to the inability of the DRPS to include lifts in solution evaluation. This lift is intended for use in evacuation [43] so this is a further concession in terms of realism. Maps displaying the real building layout of the ground floor to 4th floor, inclusive are shown in appendix 2. The stairwells have a range of protection levels, with the 2 left most stairwells being protected by doors and entrance vestibules on all but the 1st floor. The right hand pair of stairwells are protected by doors on the ground floor, but are otherwise unprotected other than the right most stairwell on the 3rd and 4th floors, which has protection from a door and entrance vestibule.

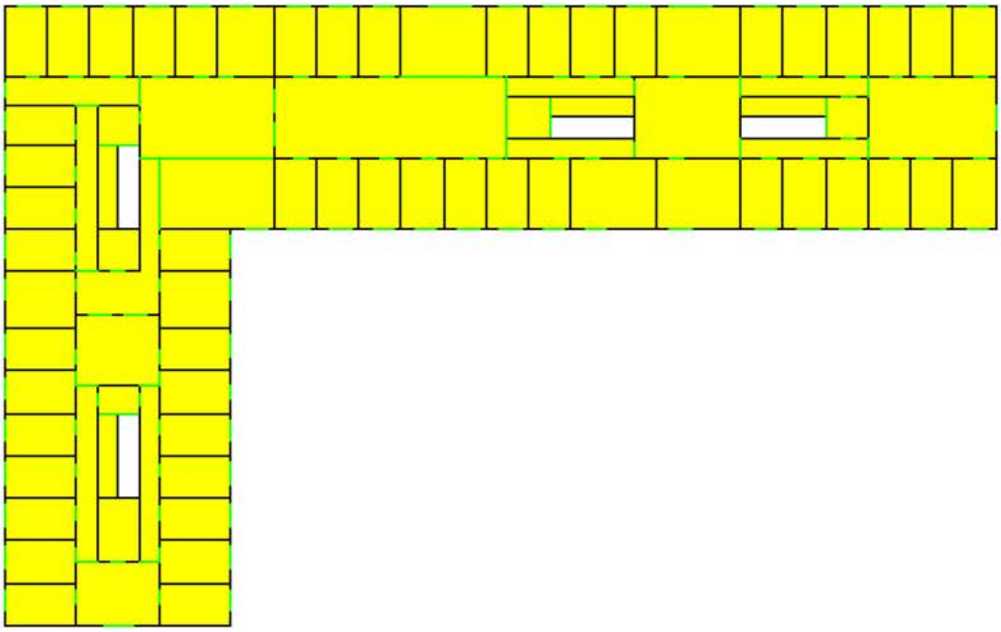

Figure 5-1 - Simplified room layout for 50 George Square 4th floor

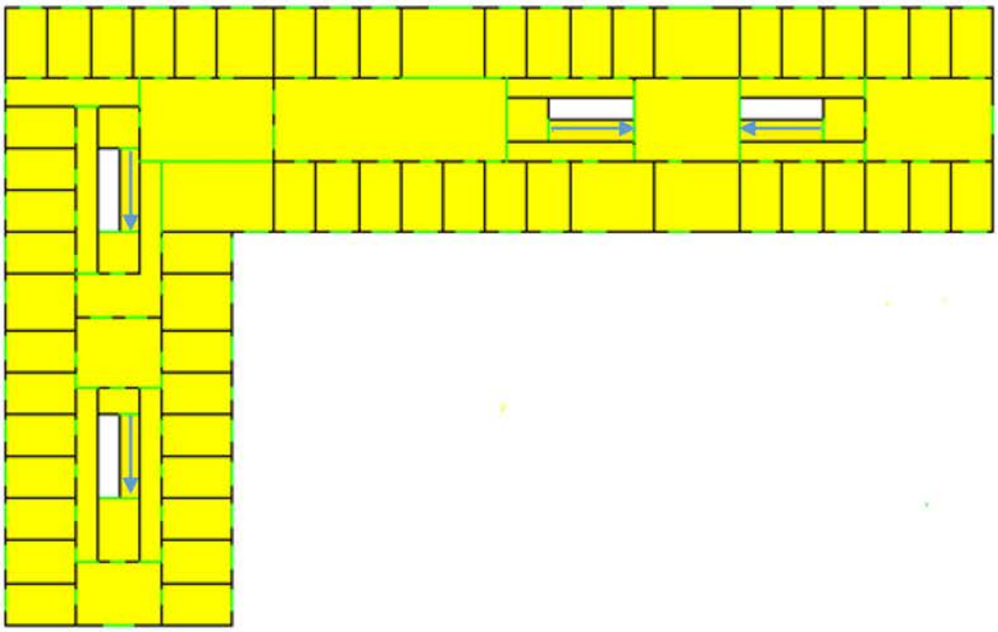

Figure 5-2 - Simplified room layout for 50 George Square 3rd floor

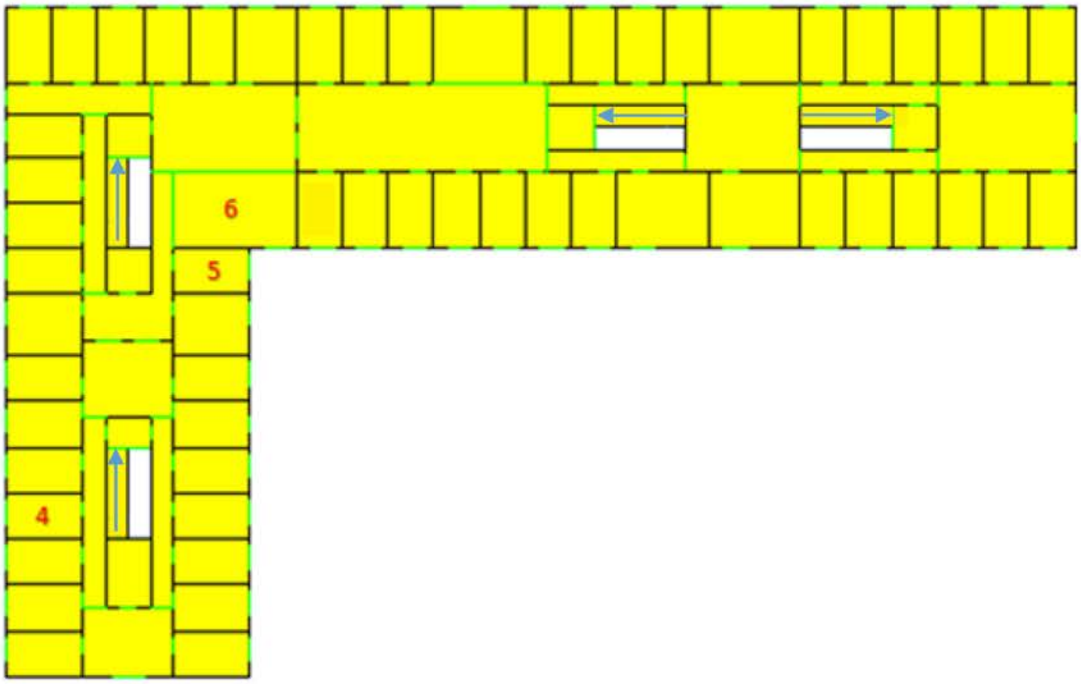

Figure 5-3 - Simplified room layout for 50 George Square 2nd floor.

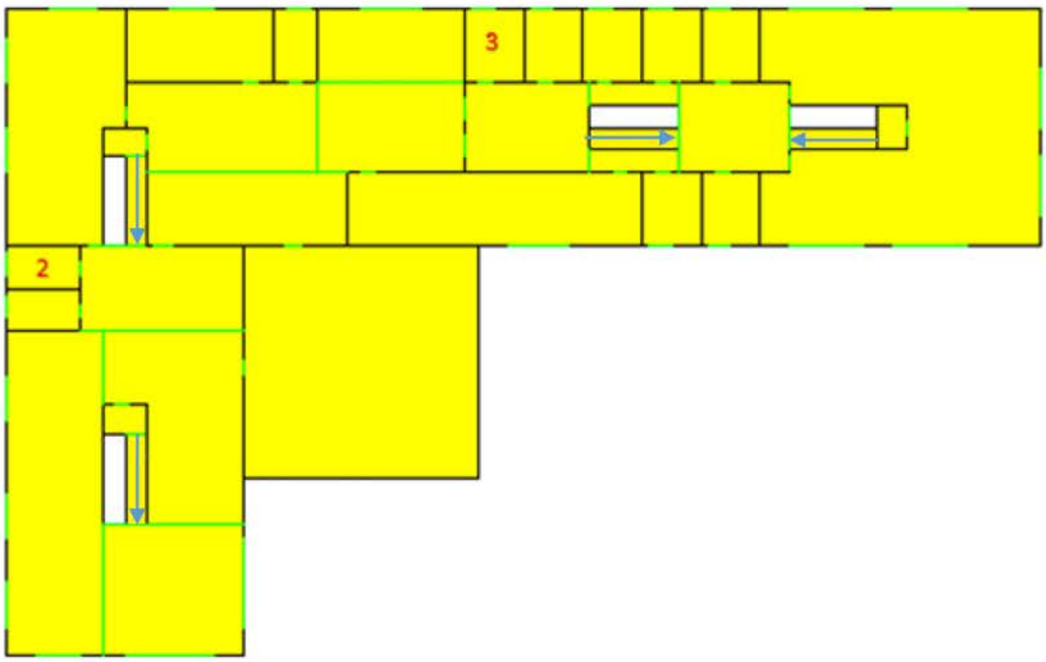

Figure 5-4 - Simplified room layout for 50 George Square 1st floor.

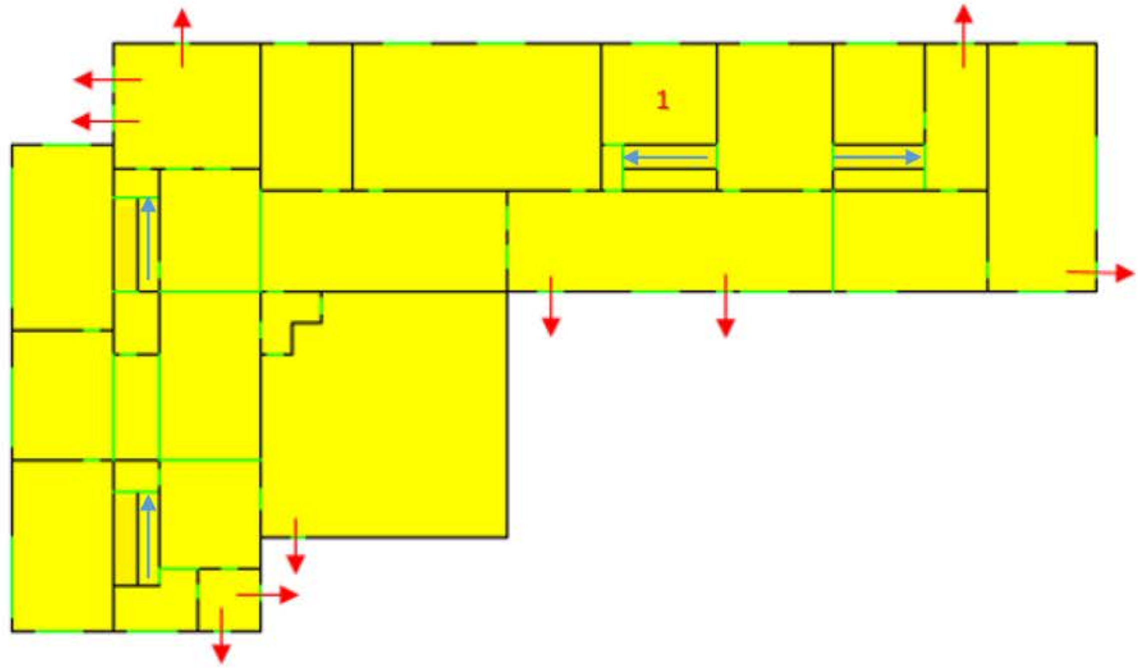

Figure 5-5 - Simplified room layout for 50 George Square ground floor. Red arrows represent exit doors.

The red arrows in Figure 5-5 refer to exit doors and the blue arrows in each figure represent upward stairwells pointing in the direction of increasing height. The red numbers 1-6 represent each discrete fire location and the possible fire load at each location consisted of a sofa, TV, papers, waste paper bin and electrics, where the initial burning object was the sofa on each occasion.

Detectors were located in open spaces and corridors throughout the building in a similar style to the previous chapter, in addition to larger rooms on the ground and 1st floor. For each of the 6 possible fire locations, 2 different sets of initial conditions were considered with each of these being repeated 3 times for a total of 36 simulations per test type. No fires on the 3rd or 4th floors were considered in this chapter as the results from the previous scenario had shown that it was fires on the lower floors that provide the more challenging environment for the DRPS to achieve safe evacuation and as such are of greater interest.

The total number of occupants within the building at initiation was 500 for all simulations. The two lecture theatres on the ground and 1st floors are assumed to contain a higher proportion of occupants than the office rooms throughout the remainder of the building. These are identified by the large square rooms in the apex of the overall building layout and 24% of the total population were initially located within these compartments. The remaining 76% were randomly distributed throughout the rooms of the building with no weighting given to any particular area. These population distributions are estimates, as it was not considered necessary to obtain exact distributions for this system demonstration, as many other simplifications were also made.

As per previous chapters; the following assumptions are made:

- Once an occupant has evacuated the building they will not attempt to re-enter.
- It is impossible for detectors to malfunction.
- All occupants are considered to be awake from the beginning of the simulation.
- Although windows on floors below the 2nd can be used by occupants to evacuate, they are never considered in the DRPS and therefore will never be instructed to use them.

5.2 Test Type Explanation

This section describes the various test types that were used during simulated evacuations. Each steered evacuation is identified by a steering type and the number of evaluated solutions per system execution.

> **Dynamic Steering** - Upon an alarm being activated, a set of path instructions are generated using the sensor data available at that time. These instructions

are revised at certain time intervals for the duration of the simulated evacuation to respond to the evolving scenario. Multiple execution run.

Static Steering - Upon an alarm being activated, a set of path instructions are generated using the sensor data available at that time. These are not updated for the remainder of the evacuation. Single execution run.

Universal Fastest Path (UFP) - Each occupant is instructed upon the shortest available safe path. This will adhere to rules regarding conservation of path direction and priority, where possible. Single solution execution.

Multiple Solution Run (MSR) - The system will evaluate a defined number of solutions for each system execution, selecting the safest or fastest equal safest.

Alarm Activated Evacuation (AA) - No path instructions are sent to the occupants but upon an alarm being activated all occupants have their actions set to “escape” and target room set to “outside”. The path which the occupant takes is defined by the CRISP behavioural and route finding rules. The purpose of this test type is to remove the difference in pre movement time between steered and un-steered evacuations, thus allowing focus on comparing occupant selected routes with DRPS selected routes.

5.2.1 Steered by DRPS

- Dynamic Steering, Multiple Solution Run.
- Dynamic Steering Universal Fastest Path
- Static Steering, Multiple Solution Run
- Static Steering, Universal Fastest Path

5.2.2 Not steered by DRPS

- Alarm Activated Evacuation

It should be noted that due to the results obtained in previous scenarios and limitations in the CRISP model varied obedience and totally un-steered tests were not carried out in this chapter. Specifics of the layout of the building resulted in permanent blockages sometimes occurring during evacuations with un-steered occupants and thus obtaining reliable results from test types with un-steered or disobedient occupants wasn't possible. An example of such a situation is shown in Figure 5-6 where a blockage has occurred on the third floor. In this situation there is a fire on the 2nd floor that is near the stairwell in question. Occupants are attempting to leave the entrance to the stairwell as they have perceived the hazard on the floor below (downward stairwells not displayed on the map of each floor) but many other occupants are also trying to gain the stairwell entrance as they have not yet perceived the hazard. These two factors result in a traffic jam that was not resolved. This highlights a limitation of the CRISP model but previous results give justification for omitting such test types as steered simulations even with low obedience levels generally resulted in safer evacuations than AA or un-steered evacuations. In addition to these omissions, due to the failings of speed and area adjustments to enhance evacuation safety in the previous scenario, this was not considered in this chapter. Pre-movement times were not considered in this chapter as there were no tests with un-steered or disobedient occupants.

For dynamic MSR tests, the number of generated solutions is 100 for the first system execution and then reduced to 10 for subsequent executions. Due to the substantial increase in building complexity when compared with previous scenarios, the time required for generation and evaluation of 100 solutions becomes significant enough to be detrimental for achieving near real-time steering. Decreasing this number to 10 allows for some of the advantages associated with multiple solution generation to be conserved while maintaining the goal of the system being effective in near real time. For static MSR tests, 100 solutions were generated and evaluated.

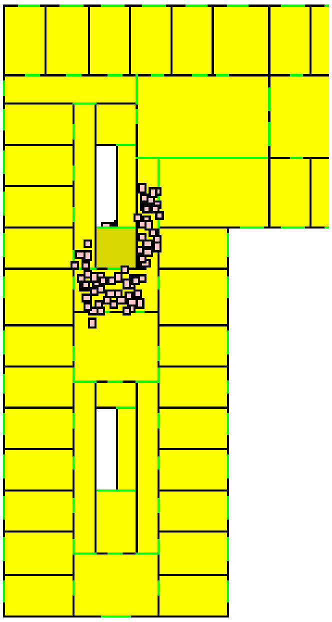

Figure 5-6 - Example of possible blockages that could occur in this building layout.

5.3 Results and Discussion

The difference in overall safety between steered and un-steered evacuations has already been established in the previous two chapters but the effectiveness of MSR steering compared to UFP steering has not and as such this comparison was the main area of interest for this scenario. Up to this point in the project, dynamic steering has proven more effective than static steering in more complex situations and where there was greater danger to life (i.e. a more dangerous fire). This was as expected but confirmation was required that this trend would continue for this more realistic scenario.

Table 5-1 and Table 5-2 display the overall results for all scenarios, with each numbered heading referring to each discrete fire location. The overall FED results are shown in graphical form in Figure 5-7 to Figure 5-10 inclusive.

Average Total FED							
Test Type	**ALL**	**1**	**2**	**3**	**4**	**5**	**6**
DYNAMIC MSR	1.82	0.26	0.07	2.60	0.11	5.87	2.01
DYNAMIC UFP	2.87	0.27	0.32	2.75	0.57	8.68	4.67
STATIC MSR	9.07	21.37	16.09	4.05	0.48	6.62	5.83
STATIC UFP	8.22	28.10	0.35	6.87	0.18	4.53	9.29
AA	31.83	30.94	81.85	10.09	0.59	52.62	14.89

Table 5-1 - All Total FED results

Average Maximum Individual FED							
Test Type	**ALL**	**1**	**2**	**3**	**4**	**5**	**6**
DYNAMIC MSR	0.12	0.15	0.00	0.17	0.05	0.27	0.08
DYNAMIC UFP	0.13	0.10	0.05	0.20	0.05	0.20	0.20
STATIC MSR	0.51	1.35	0.88	0.25	0.05	0.25	0.25
STATIC UFP	0.46	1.75	0.05	0.43	0.05	0.15	0.33
AA	1.81	4.20	3.50	1.20	0.05	1.35	0.55

Table 5-2 - All Individual FED results

In summary, once again, when all results were considered, static steering proved to be a less effective method than dynamic for both MSR and UFP tests. AA tests, once again, also resulted in the highest FED levels.

In terms of absolute FED levels when compared to the previous chapter there were opposing factors involved. The increase in population from 300 to 500 was expected to increase the total FED levels, as was the greater overall evacuation times involved (both total and 50%). On the other hand, the spaces occupied by the population during evacuation were more open than in the previous scenario which would suggest that these spaces would take longer to become inundated with dangerous smoke. This would suggest that fewer occupants would be trapped in a dangerous situation for a significant period of time. The stairwells here were also generally much better protected than in the previous scenario although if they do become compromised, especially during static steered tests, then occupants will be spending longer to travel down these stairwells due to the greater number of floors.

The results showed overall lower FED levels for Dynamic and AA tests in this chapter than for the previous but the opposite is true of static steering even when adjusting for increased population. This would suggest that the factor involving the longer required stairwell travel resulting in longer exposure in the event that a stairwell is compromised; had a major effect. The comparably lower dynamic test total FED results show that the greater choice of stairwells available for egress as well as the larger quantity of available non-hazardous space is the dominant factor when occupants' route instructions can be adjusted appropriately to the evolving scenario. These described trends were repeated with consistency for individual FED results.

When considering the results from this chapter on their own, an interesting contrast has occurred. Overall total FED results show MSR steering is more effective than UFP for dynamic tests but not for static tests, where the opposite is true. The discrepancies between each are roughly equal and the trend is also repeated for individual FED results. As dynamic MRS steering resulted in the safest evacuations, these results were positive for increased DRPS sophistication improving safety, as this is the most advanced steering type that does not rely on pre-gathered data. In the previous scenarios this was not the case, to such an extent that dynamic MRS steering was not investigated in detail. However, to determine the reason behind these trends it is necessary to further investigate the effect of the location of fire origin.

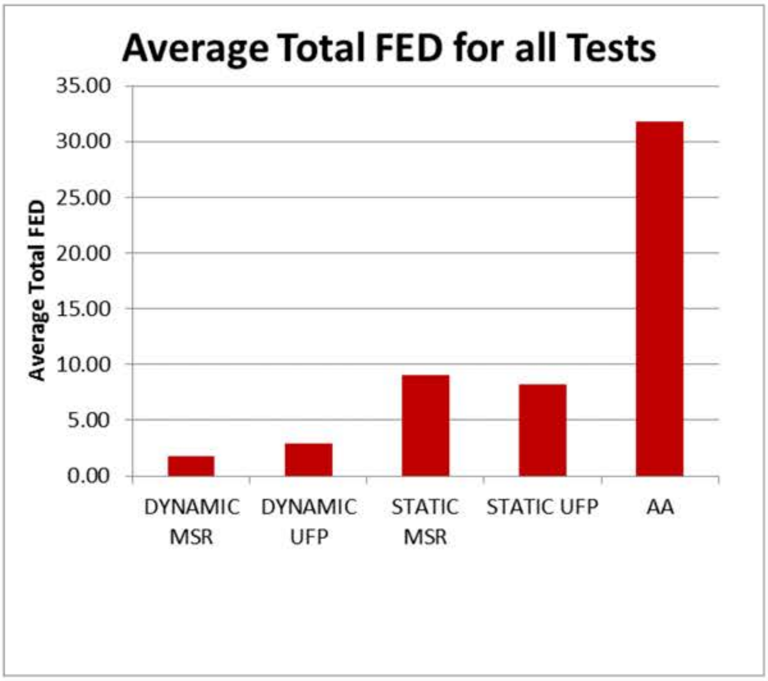

Figure 5-7 - Average Total FED for all tests

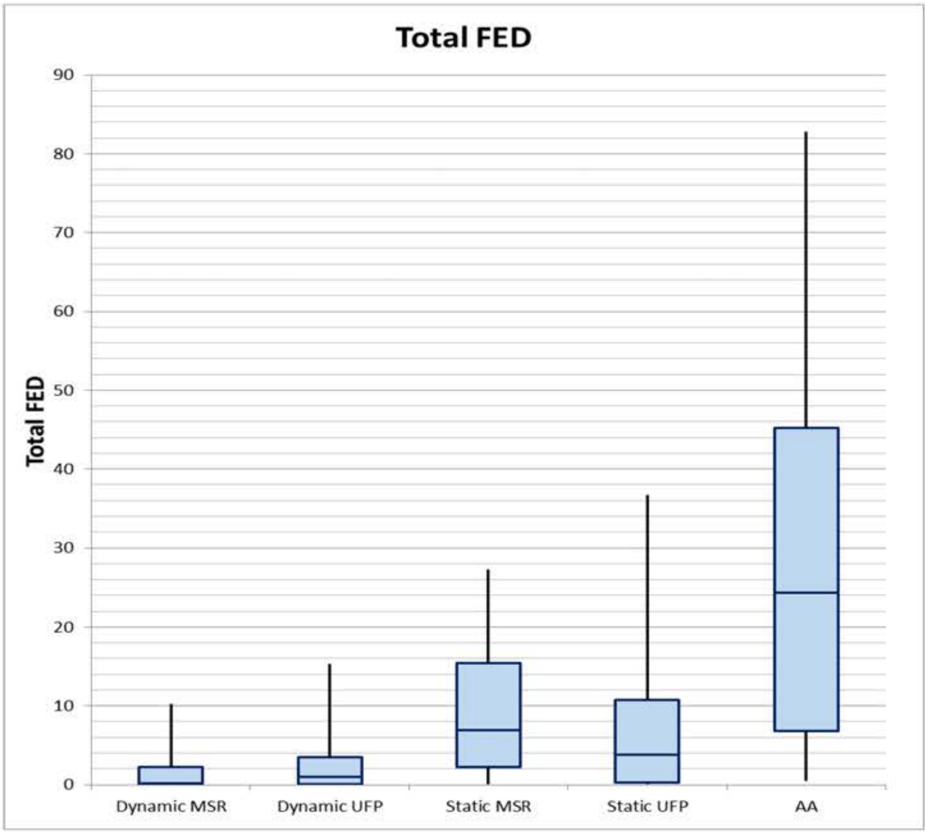

Figure 5-8 - Total FED

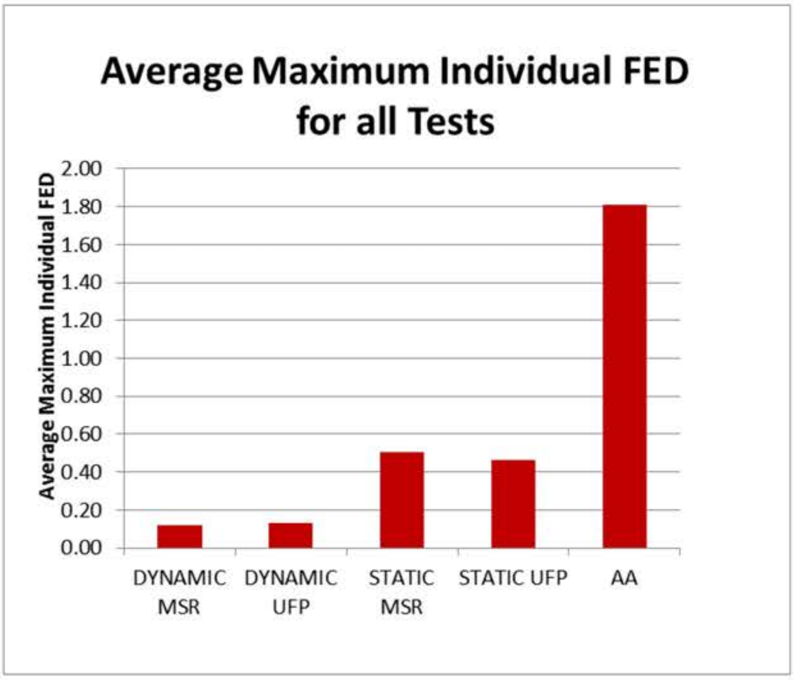

Figure 5-9 - Average Maximum Individual FED for all Tests

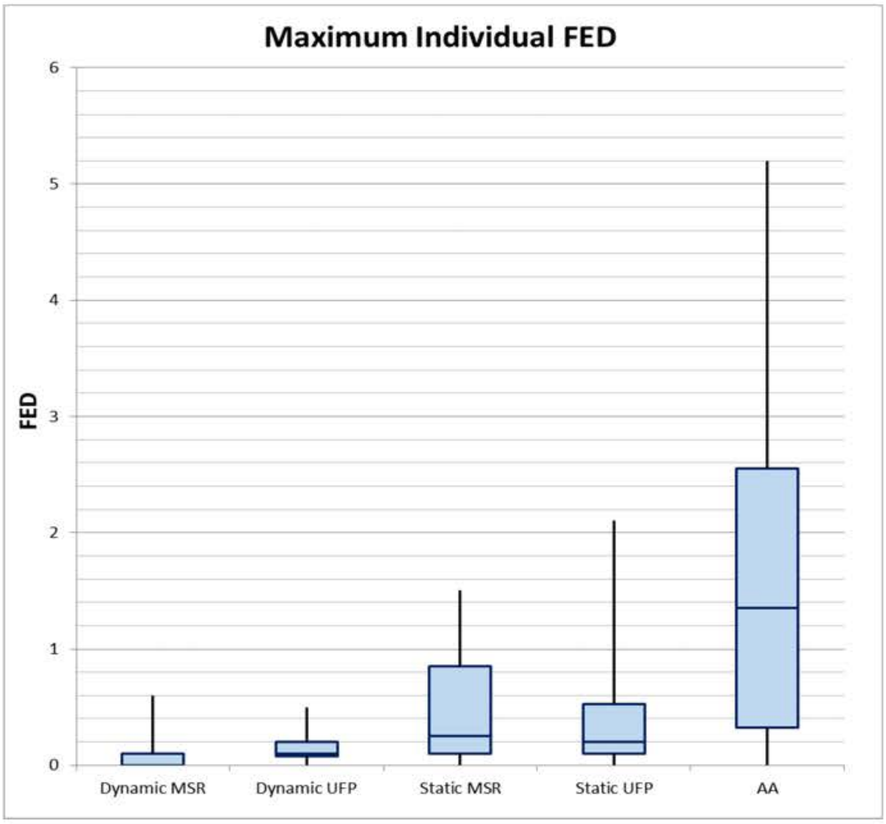

Figure 5-10 - Maximum Individual FED

Each discrete fire location impacted differently in terms of the number of effected egress routes (especially stairwells) and how quickly this will have occurred. The time until detection will also have had an influence on the overall results as this is when the DRPS will have initiated. A fire at fire location 1, as shown in Figure 5-5, had a very significant impact that will have materialised quickly, on the stairwell adjacent to the room as this stairwell was not protected by a door other than the single one leading from the room of fire origin itself. As this is also on the ground floor the effect will be throughout the entire height of the stairwell. It was also possible that the fire would affect the other stairwell in the same half of the building. This fire at this location was consistently the earliest to be detected at around roughly 55 seconds from initiation (exact detection times vary simulation to simulation). This location had the fastest detection time of all because there was a detector within the room of fire origin and this is the only instance where this was the case.

The two exits to the outside from the open space adjacent to the fire location were also affected but there was relatively little effect on the other half of the building as there is a doored wall giving protection.

Fires originating at location 2 (Figure 5-4) will have a profound impression on the use of one stairwell which will be compromised as soon as smoke escapes from this room. There is also a second stairwell further down the building which is not protected on this floor that was also compromised but at a later time in the simulations. Detection times for this fire location were significantly longer than for location 1 at consistently over 100 seconds. Being on the 1st floor the fire here will still have affected a large proportion of the building's occupants' egress routes but fewer than location 1.

Location 3 (Figure 5-4), which is also on the 1st floor, fires will have had an influence on the 2 stairwells in its half of the building although not as quickly as location 2 fires had on the nearest stairwell to it. The effect on these two stairwells is likely to have been quite similar due to the direction in which the entrances are facing. Detection time for this fire location was consistently around 93 seconds.

The remaining fire locations reside on the 2^{nd} floor (Figure 5-3) so they should have affected a lower number of occupants than the previous 3 locations. Location 4 fires will only have affected 1 stairwell and this may not have occurred quickly as this stairwell has better protection than some others. However the entrance to this stairwell is cramped when compared to several of the others so it would have been possible for occupants to get stuck trying to utilise the stairwell and as such have their location compromised by smoke while being unable to escape quickly. The detection times varied significantly but consistently between the two different initial condition set ups that comprised this fire location. One initial condition would result in a detection time of around 95 seconds and the other varied between 130 and 150 seconds. This can be explained by there being an occupant initially located within the room of fire origin for the simulations where there is a lower alarm activation time, as they will have evacuated the room and left the door open in the process, accelerating the smoke propagation.

Fire location 5 and 6 are both in very similar locations and would have had a profound impact on their nearby stairwell although, due to the partition walls on either side, this was likely to be the limit of their effect. The major differences between these fire locations are how quickly the fire will be detected and how quickly the ensuing hazard will propagate. Location 5 is an enclosed office room and the detection times for these fires varied 96 to 150 seconds due to the factors mentioned for location 4. Location 6 on the other hand is in an open space and as such the detection time and speed of smoke spread was expected to be much faster. The detection time for this location was around 72 seconds being consistently the 2^{nd} quickest after location 1, which had a detector in the room of fire origin.

Fire location 1 resulted in a very large difference in FED levels between static and dynamic steering with the static steering nearly producing as high levels as AA tests (Figure 5-13 and Figure 5-14). The relatively low FED levels produced by the dynamic tests can be explained by the fact that the left two most stairwells will remain safe so if the rightmost stairwell is compromised (the stair next to the fire origin was defined as hazardous when the initial route instructions are given) any occupants that were originally instructed to use this stairwell can be re-directed. An example of this occurring is shown in Figure 5-11 and Figure 5-12 where at the earlier stage in the simulation the stairwell nearest the fire is deserted but at the later stage, smoke has reached the rightmost stairwell while it is still in use.

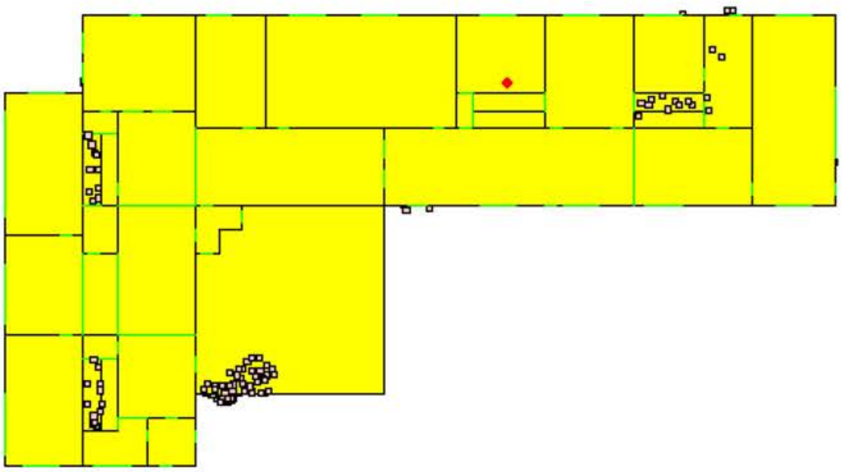

Figure 5-11 - Ground Floor at 80 seconds into simulation.

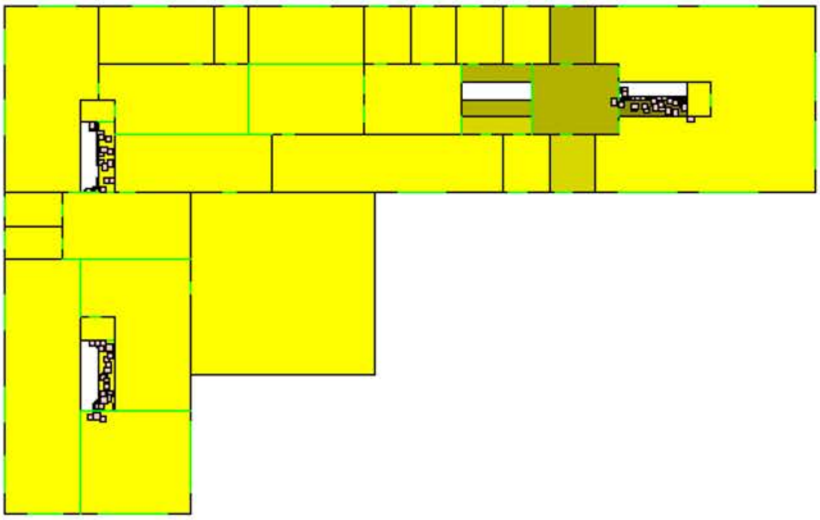

Figure 5-12 - 1st Floor at 180 seconds

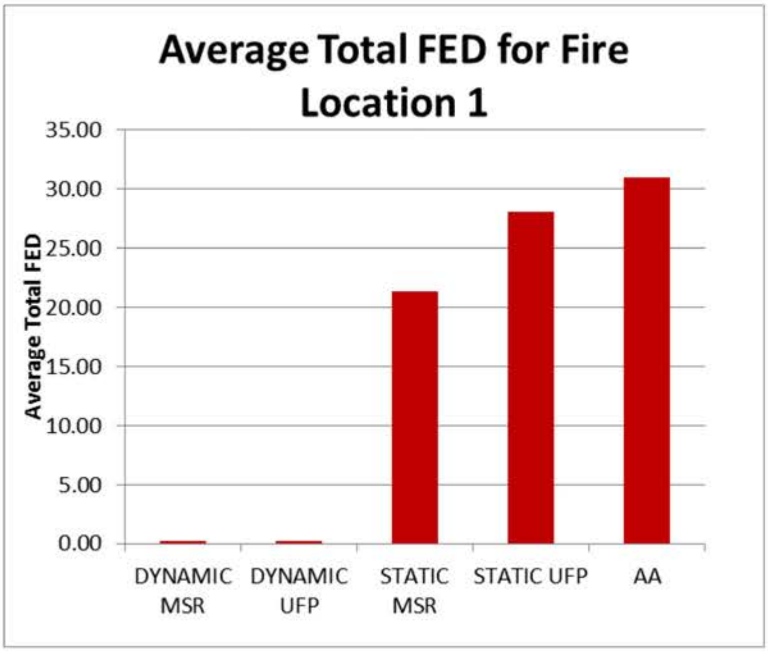

Figure 5-13 - Average Total FED for Fire Location 1

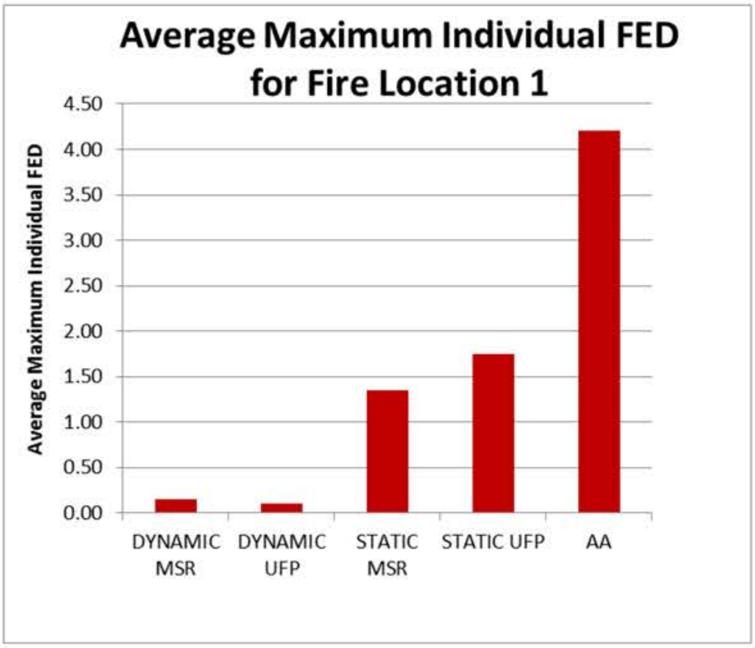

Figure 5-14 - Average Maximum Individual FED for Fire Location 1

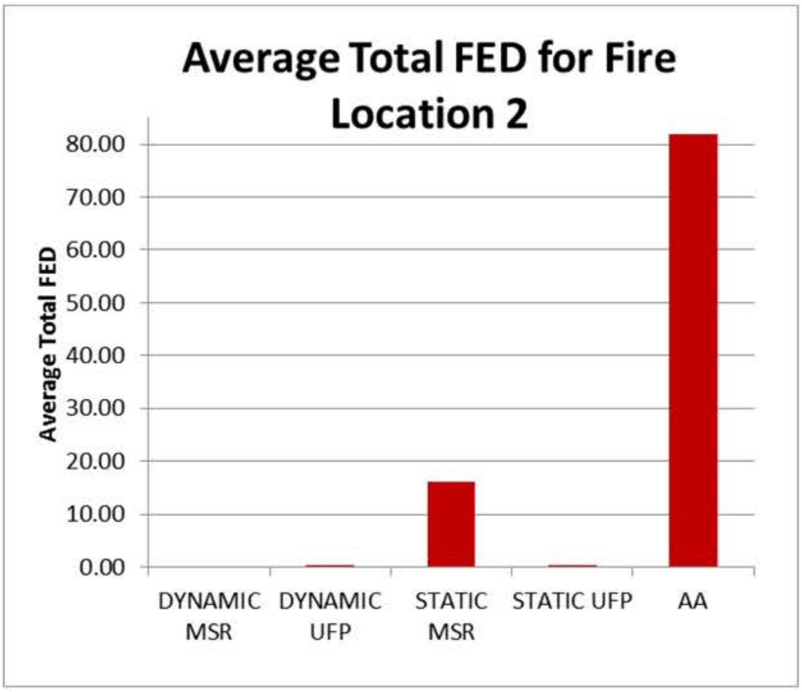

Figure 5-15 - Average Total FED for Fire Location 2

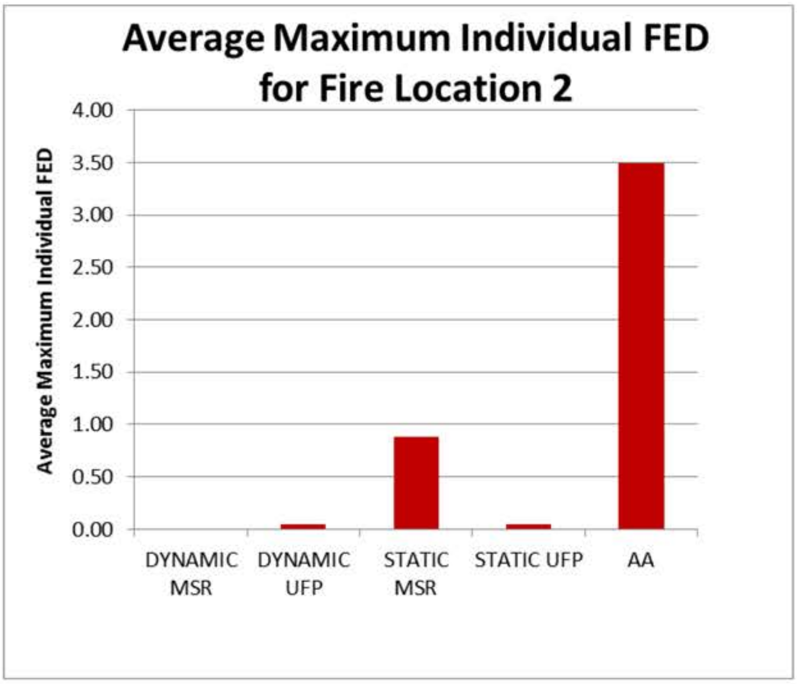

Figure 5-16 - Average Maximum Individual FED for Fire Location 2

Location 2 fires resulted in very low FED results for both dynamic tests types as well as static UFP but high FED for the remaining tests (Figure 5-15 and Figure 5-16). Dynamic MSR proved to be the safest steering method once again which likely due to the right hand side of the building providing a safe avenue evacuation throughout the entire simulation. The very high AA test FED results can be attributed to the close proximity of the room of fire origin to a stairwell, combined with the longer detection time.

Location 3 fires resulted in a similar trend to location 1 with increased DPRS sophistication resulting in improved overall safety (Figure 5-17 and Figure 5-18). However the difference between static and dynamic steering results was considerably smaller (overall results for Dynamic higher than for location 1, with static being much lower). Upon alarm initiation, no stairwell was deemed hazardous which will have resulted in the two stairwells that are clearly at risk of being compromised at a later stage in the simulation having their evacuation loads fairly evenly distributed, decreasing the required time to clear all occupants. When this did occur to both stairwells simultaneously (Figure 5-19), the magnitude of the hazard is lower than for location 1 due to the egress route being further away from the fire. The combination of these factors explains the lower FED levels for static and AA tests when compared with location 1. In addition to this the fire was also one floor higher and therefore would have affected fewer occupants.

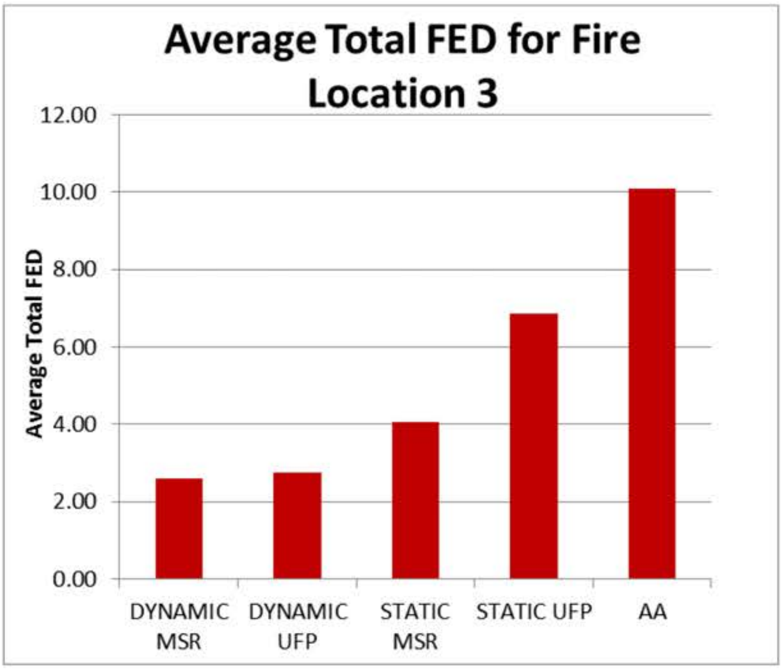

Figure 5-17 - Average Total FED for Fire Location 3

Higher FED values produced by dynamic tests are likely to be down to the same factors but with reversed implications. For location 1 fires there would have been fewer occupants being directed to the area due to one of the stairwells being initially out of bounds but for location 3 fires there would be a build-up of people in the area for when the DRPS sensors detected that the stairwells were no longer suitable. The time required for occupants to adjust their paths and clear the now dangerous areas would have resulted in the increased FED values.

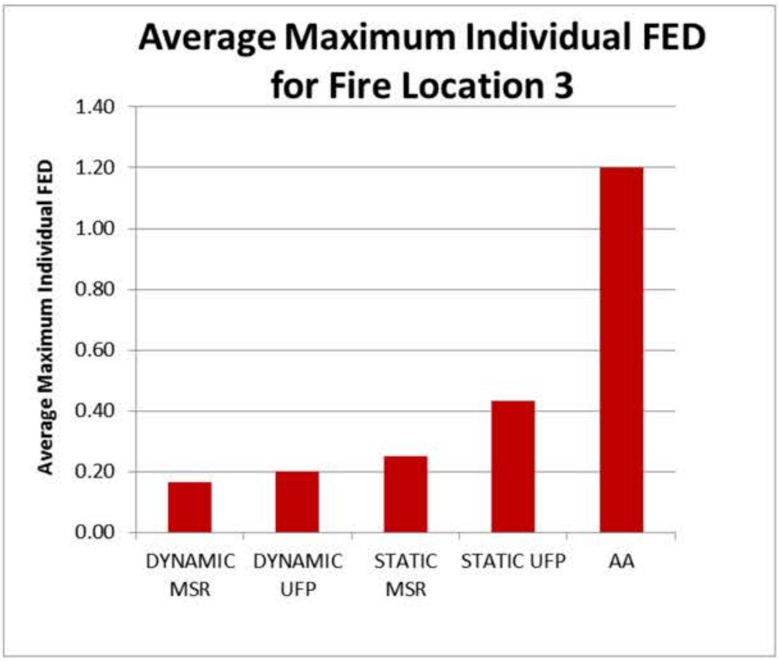

Figure 5-18 - Average Maximum Individual FED for Fire Location 3

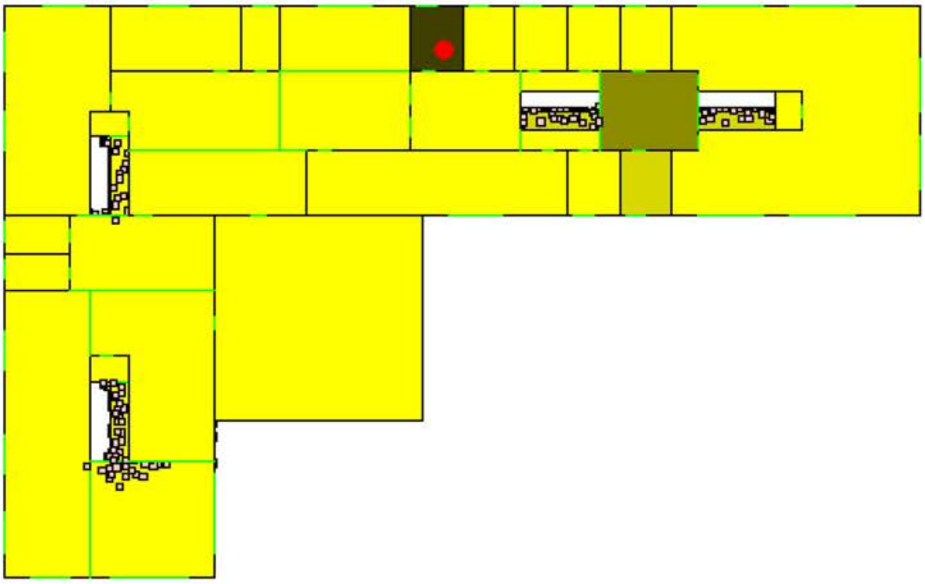

Figure 5-19 - Fire location 3 test at 190 seconds (1st Floor).

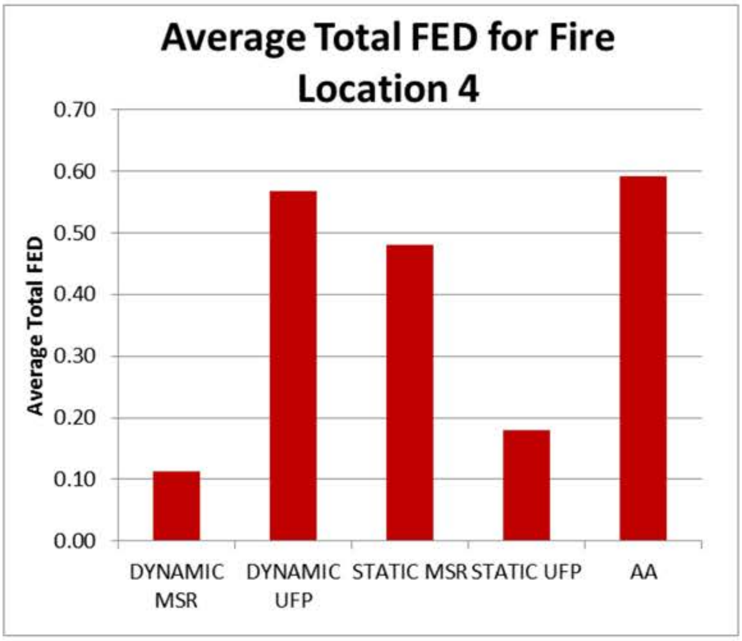

Figure 5-20 - Average Total FED for Fire Location 4

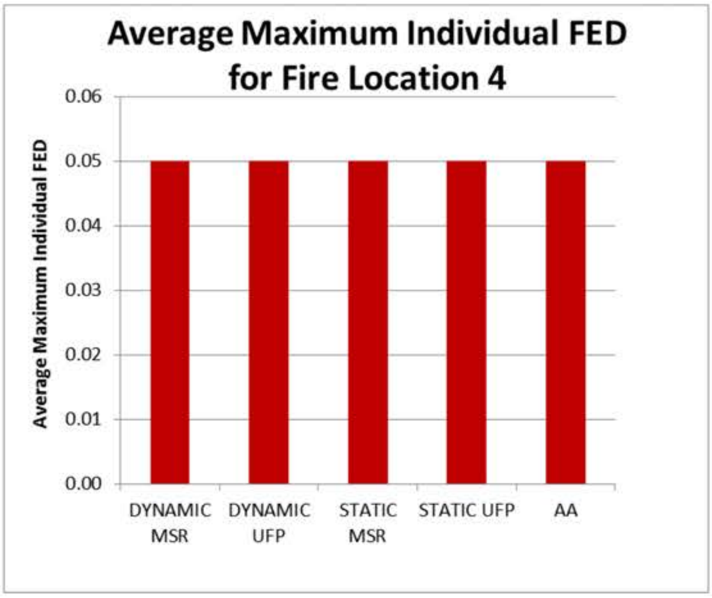

Figure 5-21 - Average Maximum Individual FED for Fire Location 4

Fire location 4 produced low FED levels (Figure 5-20) for all steering types and thus had negligible effect on the overall trends. This is reinforced by the maximum individual FED results being identical and low for all steering types (Figure 5-21).

Considering the location of the fire and how it will impact on the stairwells this result is not surprising, despite the relatively long detection time.

Location 5 and 6 fires have a lot in common in terms on initial location and but the trends in the results were slightly different (Figure 5-22 - Figure 5-25). FED levels produced by AA tests were significantly lower for location 6 which was likely due to the faster detection time, making a considerable difference to the number of occupants being present in the nearest stairwell when the conditions were at their most hazardous. The main difference between the environments the two different fires create is that location 5 initially take much longer to influence a second stairwell (both locations influence the nearest stairwell at initiation). This is explained in Figure 5-26 and Figure 5-27 where the smoke from fire location 6 has clearly travelled further after the same amount of time but more importantly towards the 2nd right-most stairwell which is more exposed on this floor than the better protected bottom stairwell.

The pattern for location 5 is similar to that of location 2 where two stairwells were initially affected by smoke, but this did not change throughout the remainder of the event. Location 5 starts with one effected stairwell but this did not increase, unlike for location fires 6. Static MSR steering appears to improve safety compared to UFP when a second (or third) stairwell is affected by smoke at a later stage in the simulation (location 1, 3 and 6) and conversely worse when this does not occur (location 2 and 5). This can be explained by considering what would happen to the proportion of the initial population near the stairwell which is effected at a later time simulation. During a UFP test, they would all, along with the occupants that start near the initially effected stairwell, be directed towards this stairwell but during MSR tests this would be lower, so when the stairwell is eventually smoke effected, it is likely that there are fewer occupants utilising it for egress. A similar comparison can be drawn between static and dynamic testing, where the dynamic results show greater improvement in safety when the situation changes throughout the simulation. This could explain the different trends between location 5 and location 6.

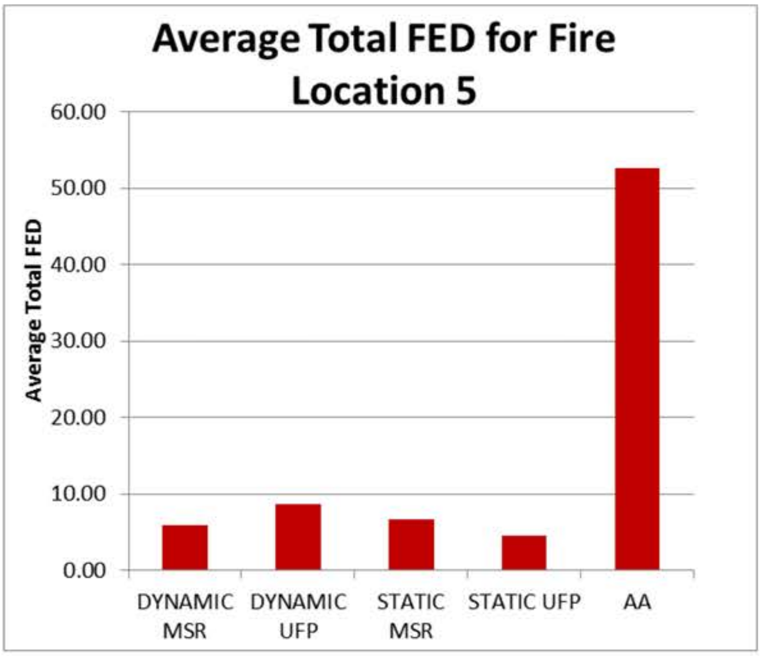

Figure 5-22 - Average Total FED for Fire Location 5

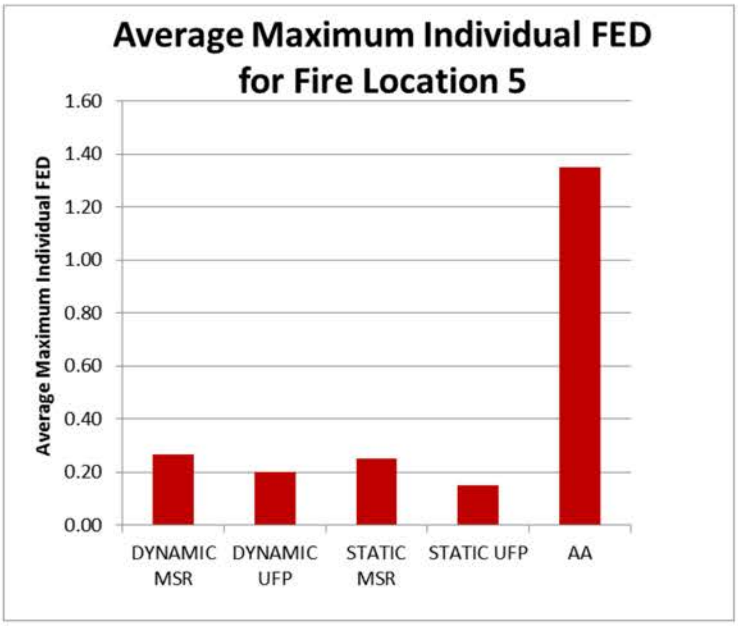

Figure 5-23 - Average Maximum Individual FED for Fire Location 5

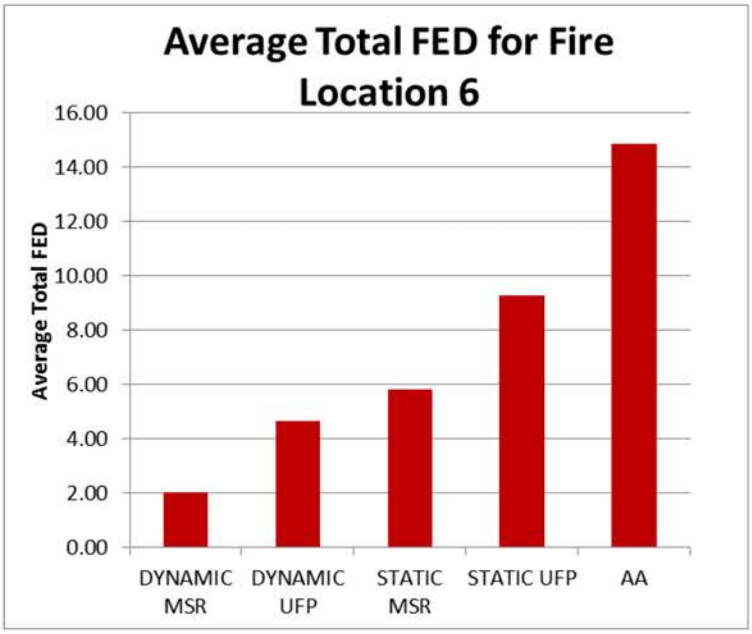

Figure 5-24 - Average Total FED for Fire Location 6

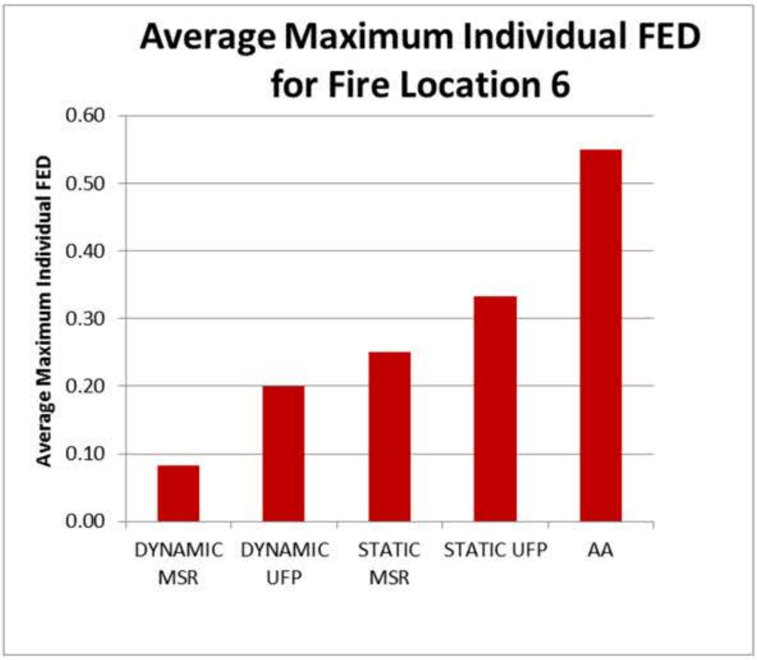

Figure 5-25 - Average Maximum Individual FED for Fire Location 6

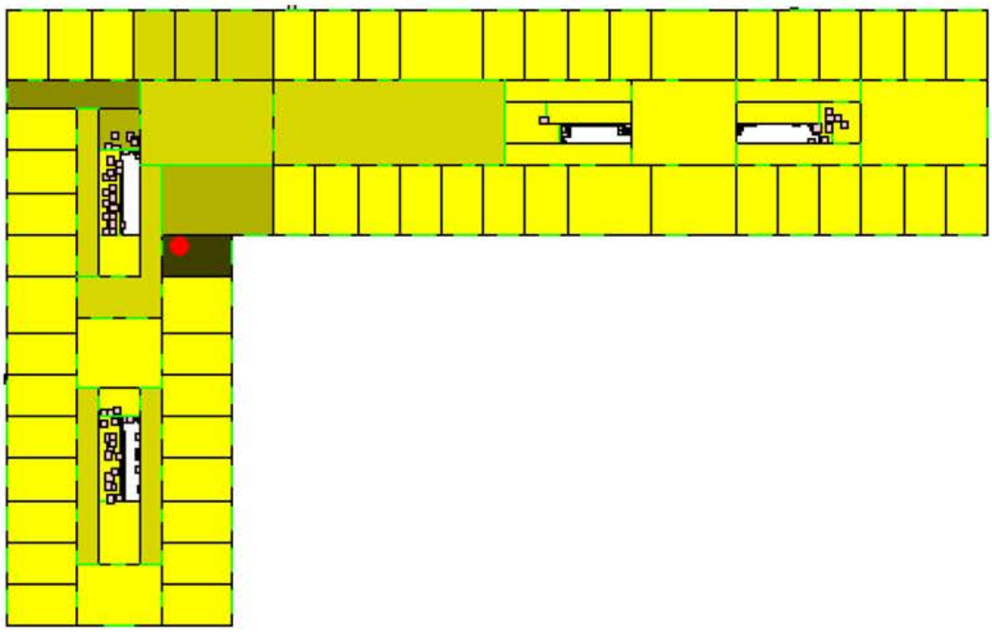

Figure 5-26 - Fire Location 5 at 180 seconds (2nd Floor)

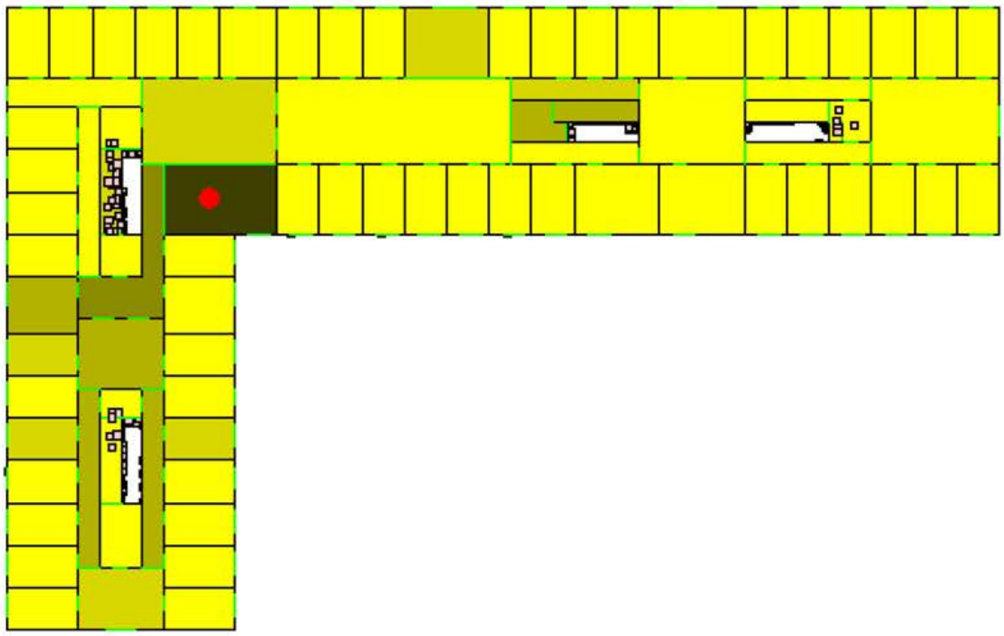

Figure 5-27 - Fire Location 6 at 180 seconds (2nd Floor)

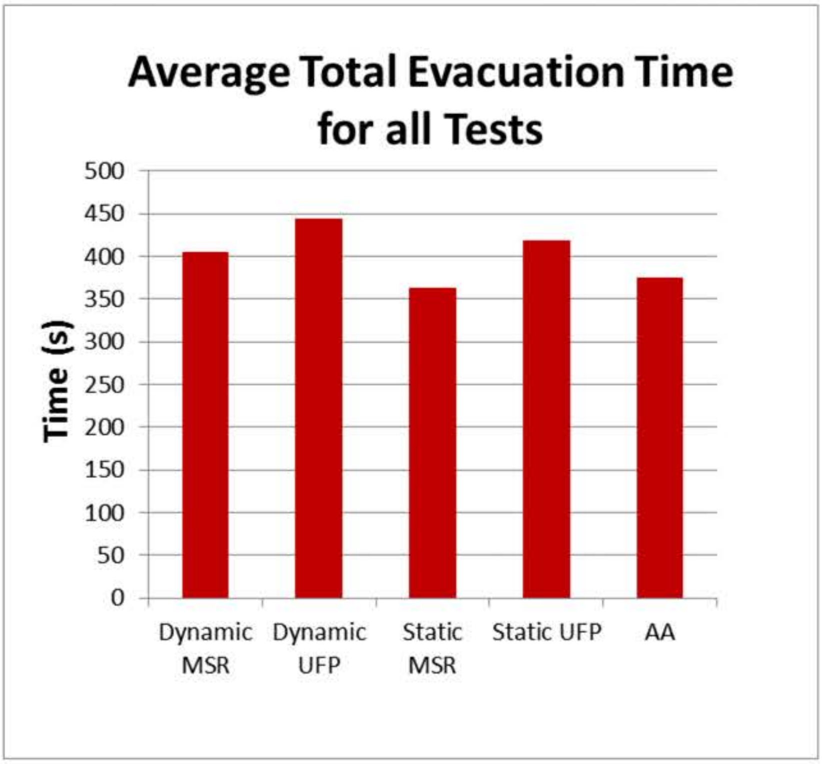

Figure 5-28 - Average Total Evacuation Time for all Tests

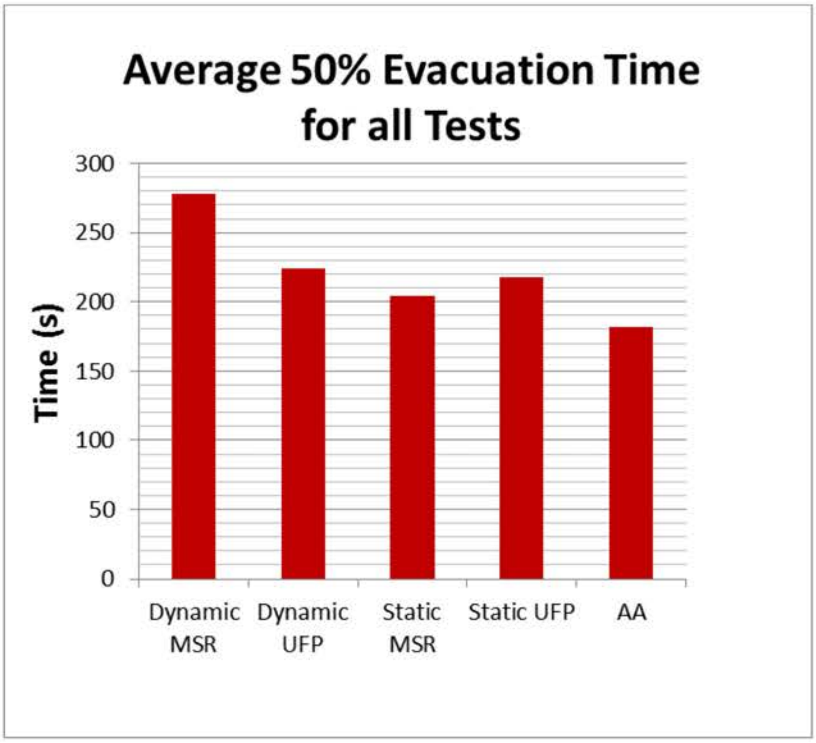

Figure 5-29 - Average 50% Evacuation Time for all Tests

Evacuation time once again proved not to be a useful measure of overall evacuation safety (Figure 5-28 - Figure 5-31). The 50% evacuation times resulted in a trend precisely the opposite of total FED levels. Total evacuation times were generally lower for MSR than UFP tests which can be explained by the increased number of stairwells meaning there is highly likely to be more than one safe option allowing the population to be spread between multiple stairwells, and thus reducing queuing. This was not the case in the scenario discussed in the previous chapter and is further evidence for the reduced number of available options from upper floors being the cause of the failure of multiple solution generation to improve safety.

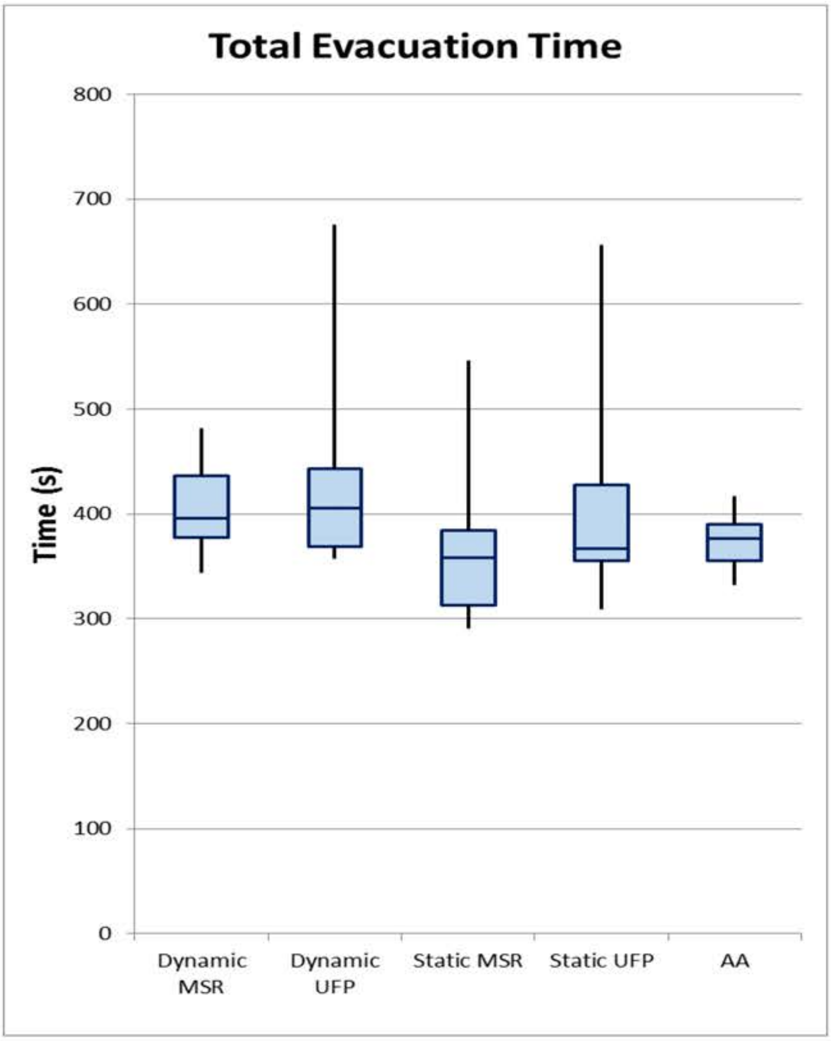

Figure 5-30 - Total Evacuation Time

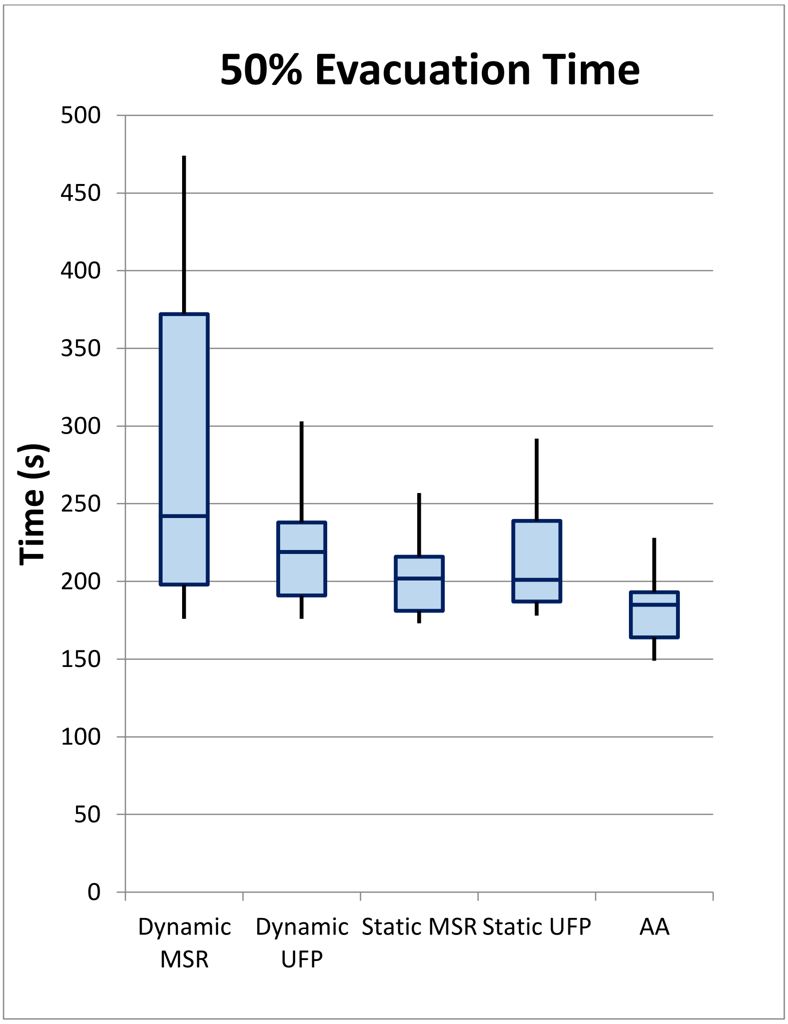

Figure 5-31 - 50% Evacuation Time

The results from this chapter provide evidence that increased DRPS sophistication leads to increased overall evacuation safety, in terms of total and individual FED across all occupants. There were some results in this chapter that suggested otherwise but these were in less challenging circumstances where the situation did not change as significantly. When increased DRPS sophistication does result in lower FED levels, the difference is by a greater margin than when this is not the case. This contradicts results from chapter 4, comparing static MSR and UFP tests, which didn't show any benefits to MSR steering. However as the building layout used in this chapter has more in common with a real building where such a system could be implemented, more weight should be attributed to these results.

6 Discussion

The goal of this project was to develop and test a novel system that is capable of improving overall evacuation safety by making use of live sensor data to generate egress route plans in real time. A range of simulated building scenarios along with a variety of occupant steering methods were tested using total fractional equivalent dose (FED) as the measure of safety. Results showed that for the adopted building layouts, this goal was achieved. This chapter aims to critically evaluate each aspect of the proposed intelligent egress system and the testing method to determine where this work fits in with existing studies and what possible continuations appear the most promising.

6.1 Scenario Design and Results

The three building scenarios used to produce the FED results throughout this project followed a trend of increasing complexity, from a simple single floor building to a 5 floor complex layout based on an existing building.

6.1.1 Scenario 1

Scenario 1 in particular lacked realism in that there were no windows and many occupants were initially placed within rooms that weren't adjacent to an external wall, which is unusual for a commercial structure. The burning object used to trigger the evacuation event was a stack of papers placed in a variety of corridor locations. This was another aspect of the scenario design that lacked realism, but was chosen as it was the only sensible fire type that could create a vaguely challenging environment in the time that was required before the building was successfully evacuated. As the average length of egress paths was low and the entire occupancy was always assumed to be awake, capable and mobile then evacuation times would be short. This, along with there being a detector in every room, would not allow for a slow growing but more hazardous room-based fire to be used (such as a sofa, or chair) in these circumstances. Different options that could have been tested to create a more challenging environment for the dynamic route planning system (DRPS) and occupants in general would include use of a material with a high heat release rate (HRR). Further possibilities include disabling of alarms or the inclusion of mobility impaired occupants. Without detectors in use, a normal object of slower fire growth rate could have been used as a hazardous environment would develop before all occupants would be alerted to the need to commence egress. Use of mobility impaired occupants was considered to be a further reduction in realism due to the layout of the building. This would be considered an option if the building resembled somewhere that elderly people would inhabit but this was far from the case here. In addition, as this was the first tested scenario and demonstration of the system it was justified to maintain simplicity. As a result of the selected options the overall FED values which resulted from this scenario were very low but usually non-zero and as such could be used for steering method comparison.

Working area and node movement speed adjustment was not employed for this scenario and all steered tests used multiple solutions (MSR) as the concept of universal fastest path (UFP) steering was an outcome of the results of this scenario and not considered before. The results showed that occupant steering did improve evacuation safety but there was little difference between static steering and dynamic steering. This was attributed to the non-hazardous nature of the environment created by the paper fire and the fact that there wasn't the required time or mass of combustible material to create a hazardous environment far enough away from the fire location to allow dynamic steering to have a positive impact on safety. Only occupants who were in a room directly adjacent to the original fire location would be forced to move near the hazard, allowing straightforward path selections to be made further negating any sophisticated aspects of the DRPS.

Due to the symmetrical nature of the building layout and inherent limitations of the DRPS knowledge of occupant location (discussed in section 6.3) an issue with dynamic steering was revealed. The path by which an occupant was being directed would often be changed if there were two paths of equal length and hazard cost available. This led to the concept of path direction conservation (section 2.4.4) being implemented in the DRPS before testing of the next scenario. It is possible that this additional functionality would have improved the dynamic compared to static results but due to the other factors relating to the benign nature of the hazard, the available room for improvement wasn't deemed significant enough to warrant repeating tests for this scenario. Moreover, the relatively non changing environment, in terms of hazard movement, also gave justification in the exclusion of UFP tests from this scenario.

A general overview of the results from this scenario suggests that influencing route choice based on sensor data and alarm activation states did result in improved evacuation safety, thus in this case satisfying the aim of the project. This was also the case for tests where 50% of the occupancy was defined as disobedient and therefore following the standard behaviour within CRISP.

6.1.2 Scenario 2

A 3-floor building where each floor was based on the layout from the previous scenario was used to provide the next testing and demonstration of the DRPS. The goal of this scenario was to produce a much more challenging situation in which to achieve safe egress, with the hypothesis that occupant steering will have a greater effect in such an environment, as well as demonstrating that increased system sophistication would further improve safety. In terms of realism the improvements over scenario 1 included the addition of windows to each room that consisted of an external wall as the use of more realistic fires. However limitations in realism remained, such as occupants being as likely to initially inhabit rooms with no external walls as they are to be located in a room with windows. Detectors were placed in the corridors and at the top of stairs, rather than in individual rooms. The range of tested fires included room based sofa fires were used along with corridor based sofa and Christmas tree fires. Each of these 3 different fires created a far more challenging environment for safe egress to be achieved. This was partly down to the increased overall egress time resulting from roughly three times the number of occupants being present as in scenario 1 although the initial population density was equal as the building was also 3 times larger.

The concept of stairwell evasion (section 2.4.2) was purposefully implemented within the DRPS for this scenario as it was obviously necessary to allow as clear a path as possible to people evacuating from the 1st and 2nd floors through one of the two stairwells leading to the ground floor. Due to the layout of the building, this was only be applicable during MSR tests as the shortest path from any room on the ground floor does not interfere with a stairwell. It was also only applicable to those on the ground floor as no path from any room on the 1st floor to a downward stairwell would interfere with a stairwell from the 2nd floor.

FED levels were generally much higher than in the previous scenario and there was a significant threat posed to the safety of the occupants. As per scenario 1, steered tests resulted in lower FED levels than un-steered and AA tests. One key difference however was that dynamic steering improved safety by a substantial margin when compared to static steering. This trend of decreased FED being provided by increased DRPS sophistication however did not continue when comparing MSR tests to UFP tests.

Specifics of the results regarding MSR (static only) tests revealed key considerations as to situation where each steering type is advantageous. MSR steering proved advantageous for instances where neither stairwell from the 1st floor to the ground floor were initially affected by the hazard but would become so at a later stage in the event. As such, the evacuating occupants would be split between these stairwells, rather than everyone being instructed to the nearest stairwell as for UFP, so when the nearer one is affected by smoke first, there will be fewer occupants queuing, and therefore exposed to hazardous conditions. This occurred during corridor based sofa fires, whereas corridor based Christmas tree fires were located in such a way that resulted in a stairwell from ground to 1st floor being affected from. A conclusion that can be drawn regarding this issue is that MSR steering has increased positive impact on evacuation safety when there is a situation change mid-event with respect to the number of stairwells, and thus significantly different paths, that are safe or equally safe to use.

After initial testing of Dynamic MSR steering during the development of this scenario, it was obvious that it would provide no improvement over UFP steering and therefore was not tested fully as per other steering methods. This was despite the implementation of direction conservation, with the small number of results obtained, showing a negative impact compared to UFP steering similar to that between different methods of static steering. The factors contributing to this trend were assumed to be similar to those affecting static steering, therefore leading onto the requirements of the subsequent scenario. In order to demonstrate that increased system sophistication would lower overall FED levels a more complex building layout would be required, specifically the number of significantly different path options available from the upper floors would be required to be greater.

The use of occupant movement data accumulated over many pre-run simulations to improve accuracy of predictions of how occupants move throughout the building was also investigated in this scenario, being incorporated into static MSR tests. Unfortunately the FED results produced by adjusting the working area and free movement speed at each node accordingly did not indicate any benefits thereof. For every fire type and location in this scenario, the FED results were slightly higher for adjusted speed and area tests than for standard MSR tests, demonstrating that this increase in system sophistication brought about no improvement in evacuation safety, at the very least for this building layout. An investigation into why this may be the case was carried out, the results from which are shown in appendix 1. This method of steering was not utilised in scenario 3 due to its ineffectiveness displayed in this scenario.

A summary of significant conclusions obtained from this scenario include:

- Influencing occupants' route choice reduces overall FED values compared to uninfluenced evacuations.
- If 50% of the occupancy ignores route instructions, acting as if they are un-steered, the overall FED results were consistently lower than for when no steering is used.
- Dynamic Steering results in lower FED levels than static steering.
- MSR steering has no advantages over UFP steering unless the situation changes significantly mid-scenario.
- The advantages of adjusting node working area and free movement speed using accumulated data from pre-run evacuations are at best highly limited and quite probably non-existent.

6.1.3 Scenario 3

The objective in the third and final scenario was to demonstrate the effectiveness of the DRPS in a more complex, realistic environment as well as confirming the conclusions from the previous scenario regarding where MSR steering is advantageous. For suitable realism to be achieved, the building layout was based on a real building, The University of Edinburgh building at 50 George Square. There were still limitations in realism although fewer than for previous scenarios. These included the required simplification to the building layout when implemented within CRISP and the simplistic nature of initial population distribution within the building, which is discussed below. The building also contains a lift which is designed for use during evacuation [43] but this could not be included as the DRPS lacked sufficient functionality to consider the use of lifts in solution evaluation.

Key differences when compared to scenario 2 were that there were four stairwells connecting each floor, rather than two which achieved the aim of ensuring there would be enough paths of significant difference to allow MSR steering prove advantageous. The range of possible fire locations was reduced, with only the more challenging locations being used. Limitations in the CRISP model prevented results from un-steered and lower obedience tests from being obtained. However as the benefits of occupant steering even with 50% obedience levels had been conclusively demonstrated in the previous chapters, this issue was not considered significant enough to change the scenario design.

The method by which path instructions are interpreted by CRISP required modification for this scenario due to specifics of the building's room arrangement. It was possible for an occupant to be a significant portion of the way along their instructed egress path, while still correctly following the path, and to then end up in a CRISP room that did not form part of this path. An example where this situation could occur is shown in Figure 6-1. As the occupant enters the second CRISP compartment on their path, the next target room will be the long, vertical corridor section and as such the perfectly reasonable option of passing through the additional open compartment, which is not on the instructed path, becomes available. When the steering algorithm checks whether this occupant requires their target room to be changed, if they have taken the alternative route, it will not be possible to determine what step on their path they are now on. The occupant is effectively "lost" according to the system although the actual detriment to the system effectiveness posed by this issue was minimal. This issue which would arise regularly throughout testing due to the nature of the building layout was resolved by setting the next room on the occupant's path to the stairwell that would have been next on their originally instructed path. In this instance, it would have been possible to bypass this problem by redesigning the room geometry within CRISP, but it was considered a useful addition to the system as similar issues could arise in any future applications of the DRPS.

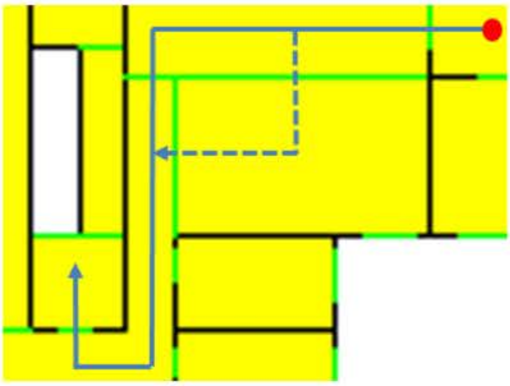

Figure 6-1 - Example of where occupant can incorrectly follow their instructed path. The red dot represents occupants initial position, the solid blue line is their instructed path and the dotted blue line is the possible incorrect, but acceptable alternative.

Dynamic MSR was the most sophisticated steering method used in this project and by resulting in the lowest overall FED levels for scenario 3, the aim of demonstrating increased DRPS sophistication would improve egress safety was satisfied. Whether static MSR or UFP tests provided the lowest FED levels, was dependent on the fire location. The results were consistent with those in scenario 2 regarding whether or not the situation would change significantly throughout the simulation. If a second (or third) stairwell was compromised by smoke part way through a scenario that was not initially affected, then MSR steering would result in lower FED levels. Dynamic UFP steering remained superior to all static steering in most cases, and overall, but dynamic MSR was more effective for all fire locations.

Due to the increased complexity and realism presented by scenario 3, greater weight of importance can be attributed to the results produced by this scenario than those of previous scenarios. Therefore it is possible to arrive at the conclusion that increased DRPS sophistication results in lower FED levels in more complex, realistic building layouts when challenging and hazardous egress conditions occur. This satisfies the aim of the scenario and a significant part of the project as a whole.

6.2 CRISP Egress Model

Due to the importance of the CRISP fire-egress model to this project it is necessary to analyse the method by which it was used and compare this to previous works. One deficiency in realism that was consistent across all tests and scenarios was the simplicity of occupant behaviour used in the simulations. CRISP allows for many different occupant types with varied behavioural characteristics which affect what actions individuals take under given circumstances. The method of occupant steering employed throughout the project negated, for all steered test types with 100% obedience, most of the behavioural aspects of the CRISP egress model. Justifications for this can be established when compared to previous work with influencing egress routes within CRISP [6], which influenced egress route by defining vents leading to certain stairwells as unusable, which violates aspects of the model as shown by occupants using these vents when the system was not in use. It would have been overly challenging to successfully represent occupants responding to instructions from a smartphone, within the CRISP model, while still utilising all behavioural routines within the model. It wasn’t possible to use a strategy similar to [6] for influencing occupants on an individual basis.

Assumptions about human behaviour are a necessity within any egress model and therefore attempting to maintain all aspects of the CRISP model within these tests would not have eliminated all associated uncertainties. For this reason it was justifiable to simplify the human behavioural considerations by defining a set number of occupants for each test to remain totally un-steered. Additionally, for those occupants who were steered and following instructions would still have to use their own route planning models when considering small scale navigation, such as around other occupants and obstructions within a room. Although it was not possible to test with varied obedience for scenario 3 it was repeatedly shown in scenario 1 and 2 that when 50% of the population was obedient overall total FED levels were lower than for un-steered tests.

Weaknesses within different aspects of the CRISP model were also encountered. Instabilities in the zone mode with regards to how smoke propagates throughout the building occurred, most prominently in scenario 2, often resulting in the program crashing or producing nonsensical results. The building layout featured a large connected area of totally open corridors and stairwells which exasperated the issue. This issue was resolved by reducing the time step size during the simulation (this was originally fixed at 1 second).

A further issue where unresolved blockages occurred was mentioned in chapter 5 with an example shown in Figure 5-6. This prevented un-steered tests and those with low obedience levels being used in scenario 3 and would occur when a sufficient number of occupants would be attempting to move in opposite directions along a section of corridor or narrow passage. During early testing of the integrated CRISP - DRPS system, this would also occur as a result of people having already exited a building, attempting to re-enter. Although there are behaviour rules within CRISP that allow for occupants to warn others or generally share information, this clearly was not occurring to a sufficient extent where such traffic jams could resolve themselves. It is possible that adjusting how the CRISP rooms fit together in more complex sections of the building would reduce this issue but once again it was not deemed serious enough for thorough investigation. These limitations in the human behavioural model will have had no impact on the result of steered tests where all occupants are following instructions. However, including the possibility of occupants being able to pass information that would result in path changing for occupants that cannot directly perceive the fire would be an option for increasing the realism of CRISP.

6.3 Evaluation of Dynamic Route Planning System Components

6.3.1 Path Calculating and Storing for Complex Buildings

The method by which paths were calculated and stored started to reveal limitations as the building complexity increased. For the building in scenario 3 it was necessary to change the method slightly. When evaluating the paths from each floor each down stair from that floor was defined as safe, leading to four paths being stored from each room on the 1^{st}-4^{th} floors. After all floors' paths were calculated as far as the stairwells, the paths were collated to form complete paths from every room to the outside. The result of this change was that there were no stored paths that consisted of changing stairwell midway through egress. However, during dynamic steered tests, occupants could still be directed to another stairwell where appropriate, but only when conditions deteriorate sufficiently and not for the sake of improving general occupant flow speed (i.e. when the path down the current stairwell is no longer available due to evolution of the hazard). However the only improvements that could be achieved by using split stair paths is to lower evacuation time under circumstances of unusual occupant distribution. As dynamic steering could re-route occupants in a stairwell, to another stairwell if required, it was deemed acceptable to omit the storing of split stair paths.

6.3.2 Sensor Data Interpretation

The temperature sensor data used throughout all tests in this project is assumed to be the top, hot layer temperature in each CRISP room. As it was computed temperatures that were being used, negating any error that would be inherent in real life equipment, it was deemed justifiable for the system to be sensitive to very small temperature changes. Thermocouples are capable of operating over a sufficiently large range of temperatures [44] to a degree of accuracy that is more precise than the natural ambient temperature variation that is likely to occur in a room. Due to this variation that does not occur in the simulated environment, if the system were to be installed in a real building, the minimum temperature required for a hazard to be detected would have to be increased beyond 1 degree above ambient. No investigation was carried out in order to determine whether or not CRISP room tenability was inherently linked with upper layer temperature, although it is likely to play a significant contribution. Other stats such as various gas concentrations and hot layer depth could have resulted in a more accurate depiction of the hazard being obtained. However as the goal of the project was to demonstrate the system with limited information gathered from sensors, the possible benefits of using more detailed hazard information was not explored.

Future study may wish to investigate the use of smoke detectors, rather than temperature sensors, as the primary means of defining the hazard. Using an unlinked set of smoke detectors, with one in each compartment, would give an easier to implement means of determining which locations in a building are hazardous. This would be required to be separate from the alarm network which is required to be linked to ensure occupants throughout the whole building are aware of the need to evacuate. Smoke detectors would have the practical advantage of being able to operate without being required to detect tiny environmental changes, as per the temperature sensors being sensitive to 1 degree above ambient in this thesis. Additionally, most existing building will already have a network of smoke detectors in place. It would be relatively simple to test the effectiveness of the DRPS with hazard levels inferred from smoke detectors alone, which would give an obvious possible next step for investigation.

6.3.3 Solution Evaluation

Theoretically it could have been hypothesized that MSR steering would always result in tests with lower FED values than UFP steering, more so for dynamic tests. This is because there is always an equivalent of a UFP run in each system execution, barring for rules regarding conservation of direction and priority occupants. However this could only be the case if the sensor data allows the DRPS highly precise knowledge of occupants' location and if it was capable of perfectly predicting occupants' movement throughout the building. Neither requirement is satisfied due to the location only being accurate to each discrete room defined in CRISP. This situation can be explained by the examples shown in Figure 6-2, the first (left) of which shows a room containing multiple occupants with a single door through which all must use for egress (the second vent represents a window). The DRPS has no knowledge as to which occupant is closest and which is furthest from the door and thus any predictions about how long these occupants will require to evacuate, including how and when they will interact with those evacuating from different areas, will contain significant uncertainties. The second (right) example shows a long section of corridor with occupants scattered throughout where the DRPS will initially consider them all to be located at the same point. This resulted in the possibility of two occupants being instructed the entire length of the compartment, in opposing directions, being considered identical to the same two occupants in question being instructed along their shortest paths with regard to exiting the compartment. It is obvious, however that the resulting evacuation flow patterns would not be identical and may not even be similar. When considered over a large enough number of scenarios however, the variation of occupants' initial positons within a compartment will balance out to an average equal to the used assumed locations. It should be noted that UFP tests will instruct everyone in the corridor section in one direction, so this steering method can also produce systematic uncertainties.

Figure 6-2 - Occupant Location Uncertainties

A possible, albeit artificial, method for which these uncertainties could be minimised would be to only have 1 occupant in each room at the initiation of each scenario. The resulting low population density, if such an occupant distribution was used during any of the 3 scenarios, would have substantially decreased how hazardous the scenarios would be by allowing shorter overall evacuation times and simply not presenting a challenging enough environment to sufficiently test the DRPS. Having many much smaller compartments with one occupant initially inhabiting each one would be another option to increase the effectiveness of MSR steering but this would reduce the realism of the scenario.

Another issue that would have resulted in uncertainties within solution evaluation and therefore the chosen solution for each execution, was that the movement speed on each node at each time step was calculated without considering if all inhabiting occupants were travelling in the same direction or not. It would appear obvious that occupants travelling through a corridor section would move at a lower speed if they were in contraflow, compared to all travelling in the same direction. This consideration was never implemented within the DRPS and is a possible avenue for improvement for future works. As contraflow is far more likely to occur in MSR tests, the chances of a non base-line solution being chosen was higher than was ideal. The impact that this issue could have had on evacuation steering with regards to achieving the goals of the project, is only negative. This increases the degree of conservatism when concluding that DRPS steered evacuations are safer than un-steered evacuations and that increased system sophistication also results in lower FED levels.

This issue regarding how the flow pattern within a node does not affect the movement speed through the node during solution evaluation is likely to be a significant contributing factor to the failure of area and speed adjusted steering (AS). AA steering was used when gathering data about how population density affected the speed at each node within the building in scenario 2, where AS steering method was tested. As AA tests result in predominantly one directional flow at any single location and MSR tests often contain contraflow, this is a likely explanation of the small but consistent detrimental effect AS steering had on FED levels.

All AS testing in this project required the accumulation of movement data which, in the real world would only be available if multiple trial evacuations were performed prior to any real event requiring egress, which is clearly a limiting factor in the usefulness of such techniques. However, it is also possible to use movement data that has been accumulated up to the current point in time during the event. Obviously, this is a considerably lower quantity data to go on and specific predictions for every room are unlikely to be accurate enough to prove useful. This would however allow for significant blockages and queuing to be detected, if occupants were moving at a much slower rate than expected for the given population density, or not moving at all. Circumstances such as this could arise if large objects were temporarily left in inappropriate places in a building that wouldn't exist according to the DRPS, as it would be unlikely the system would be updated to accommodate such temporary objects after installation. Such additional knowledge would allow the DRPS to re-route occupants as required. This would appear to be a more useful approach to utilising accumulated movement data as it doesn't rely on a large amount of pre-acquired data to make small changes to node details. Therefore it is recommended that future work in this area should focus on using data acquired during a real evacuation to make changes when large differences between expected and detected movement occurs.

Pre-movement time is not considered by the DRPS, but is nonetheless a factor of real world evacuations, giving an obvious possible avenue for further development of the system. This also applies to steered occupants within CRISP, although it should be noted that in the most complex scenario using un-steered occupants (with the option of delaying evacuation); the total evacuation times were very similar between steered and un-steered tests. A method for implementing pre-movement time in steered occupants within CRISP would be to delay changing their action to "escape" by certain length of time after route instructions have been received. Actual pre-movement times, and therefore the delay to evacuation, could be input as a distribution. The likely impact of implementing this into steered CRISP occupants would be to increase FED results, as the hazard would be able to develop for longer before some occupants would evacuate.

Implementing pre-movement time within the DRPS would have to be in distribution form, as simply delaying all occupants equally would have no impact on the chosen solution, unless some form of predictive hazard model is also included. UFP steering would also not be impacted by pre-movement time in any form without the use of a predictive fire model. Moreover, dynamic steering in general can respond to occupants delaying their evacuation by differing lengths of time, by updating their instructions appropriately and when everyone has started moving, pre-movement time would no longer be a factor. It is hypothesised that the net outcome of implementing pre-movement time for steered CRISP occupants, would further improve the effectiveness of the DRPS (in its current form) in lowering FED levels relative to AA and un-steered evacuations, assuming that these also have pre-movement time included. This is because of the likelihood of higher egress times allowing more time for the hazard to develop and the smoke to propagate, creating a more challenging environment from which to evacuate. However, testing this hypothesis, especially when including a form of predicting the evolution of the hazard (section 6.4.1), would be an interesting avenue for future study of intelligent egress.

6.3.4 Conveying Route Instructions to Occupants

When considering the most effective steering method for an intelligent egress system implemented within a real building, the method by which instructions are conveyed to the occupants is a significant consideration. MSR steering, as utilised throughout the scenarios explored in this project assumes that it is possible that all occupants can be routed along paths on an individual basis, even if this involves passing two occupants in opposite directions along the same section of corridor. A method by which this is possible is the use of occupant's smartphones to provide instructions of their intended route. If, for example, changeable signage is used then it is not possible to utilise such a steering method. Conversely, UFP steering allows both steering methods to be used in the majority of circumstances (there will always be a location in a building where the direction of the instructed routes have to split). Due to well-known human behavioural traits often seen in evacuations, even with use of a smartphone the likelihood of occupants choosing to correctly follow instructions is lower when they are being directed in the opposite direction to others people in the same area than if people from the same area were to be instructed in the same direction. Due to these real world practicality issues, in addition to some of the previously discussed limitations and weaknesses within MSR steering as a whole it is necessary to discuss alternative methods for future investigation.

6.4 Areas of Possible System Improvement

6.4.1 Predictive Fire Models

Integrating a predictive fire model like those described in Chapter 1, with the system proposed in this project, is an obvious possible next step in intelligent egress. Throughout this project, all information regarding the state of the hazard is taken from instantaneous sensor data and no use of predictions of how it may progress. For example, there are many tests described where the number of safe to use stairwells, according to the sensor data, decreases throughout the event. If this was predicted in advance of the first set of route instructions being generated then lower FED levels would almost certainly be the outcome. If more complex information was sought from a sensor linked predictive fire model, such as in the care home study [20] which foretold in which individual rooms, fatalities were predicted to occur, then the benefits are more uncertain. Knowledge of the open/closed state of doors is a significant factor in determining the extent to which hazardous conditions propagate throughout the building. If occupants are evacuating then they are likely to have an affect on the open/close state and therefore how the scenario will develop. This would create difficulties for the predictive fire model as it would have make additional assumptions about how occupants would proceed, where the effect of them not doing as expected could have a much greater impact. For example, an occupant could choose a different egress route, opening a crucial door and changing the development of the hazard. This could have serious consequences for other occupants, as their route instructions were based on a substantially different predicted situation. Compare this to what would happen if an occupant were to ignore route instructions in any of scenarios tested in this project. The worst likely outcome is that the occupant would simply be adding to a queue of other occupants and slightly increasing overall evacuation time. However, a relatively simple predictive fire model, that could provide more general prediction would certainly have its place in an intelligent egress system and thus is an obvious direction for future work to go in. This is a similar recommendation to that given for utilising accumulated movement data, in that the idea is to make relatively simple but broad predictions rather than more precise predictions about every part of a building.

6.4.2 Use of Advanced Heuristics in Building Specific System

Throughout the project, while progressing between each scenario, adjustments to the DRPS functionality were required for each change in building. This suggests that if such a system were to be installed in a real building, then further adjustments are very likely to be necessary. The benefits of this are that simulated testing as per this project could be carried out to determine the most effective steering methods, or possibly even developing a unique method tailored to the specifics of the building.

When considering the building in scenario 3 it is possible that using more advanced heuristics instead, of or in addition to, multiple solution generation and evaluation would result in lower FED levels. For example, it was usually straightforward to determine which stairwells would be affected or become affected throughout the event, based on the initial fire location. Dynamic MSR steering, which produced the lowest FED levels in the majority of cases, was more effective than dynamic UFP steering due to being able to spread occupants between the remaining stairwells, as opposed to all the occupants initially near the stairwell deemed hazardous being instructed to the next nearest stairwell. Due to the solution generation for the initial execution being random, excluding the initial base-line, it is likely that additional heuristics, specific to this exact building layout could further improve safety. Moreover due to the vast size of the search space involved, the likelihood of finding an optimal or near optimal solution in real time, with the system developed throughout this project, while using modest computational resources, is vanishingly small.

A possible use of an advanced heuristic approach that could be taken in this situation that could conceivably result in lower FED values would be to have default evacuation plan in place for each room or zone where a fire could initiate. An example of how this idea could be worked into the building layout (2nd floor) in scenario 3 is shown in Figure 6-3. The large red dot represents the fire location, the diagonal red lines show the stairwell which is not considered for use due to the hazard location and the blue lines represent suggested paths for occupants in each area. The red dotted lines split the building floor plan into three areas, each of which is directed to a different stairwell, thus creating a reasonably balanced occupant load as per the advantages shown by dynamic MSR steering. There is also no point on these proposed paths where occupants in one location would be instructed to travel in different directions exploiting an advantage of UFP steering. This approach would still allow for solution evaluation to be performed as a sanity check for the evacuation plan. The option of changing the route instructions if the hazard situation evolves sufficiently is still in place. These plans would require altering when being applied to the upper floors as the bottom most stairwell could become compromised by smoke at a later stage in the simulation, therefore resulting in it being safer to direct all occupants from the 3rd and 4th floor to the stairwells in the opposite half of the building from the fire. When considering the lower floors, the stairwell nearest the hazard could be considered for use to reduce traffic on the more crucial stairwells used for evacuating the 2nd-4th floor, where there is a greater risk to occupant safety. This general evacuation plan could be also be used for fires in similar locations to that shown here and it would be possible to store a similar plan for all possible locations that are likely to create significantly different environments.

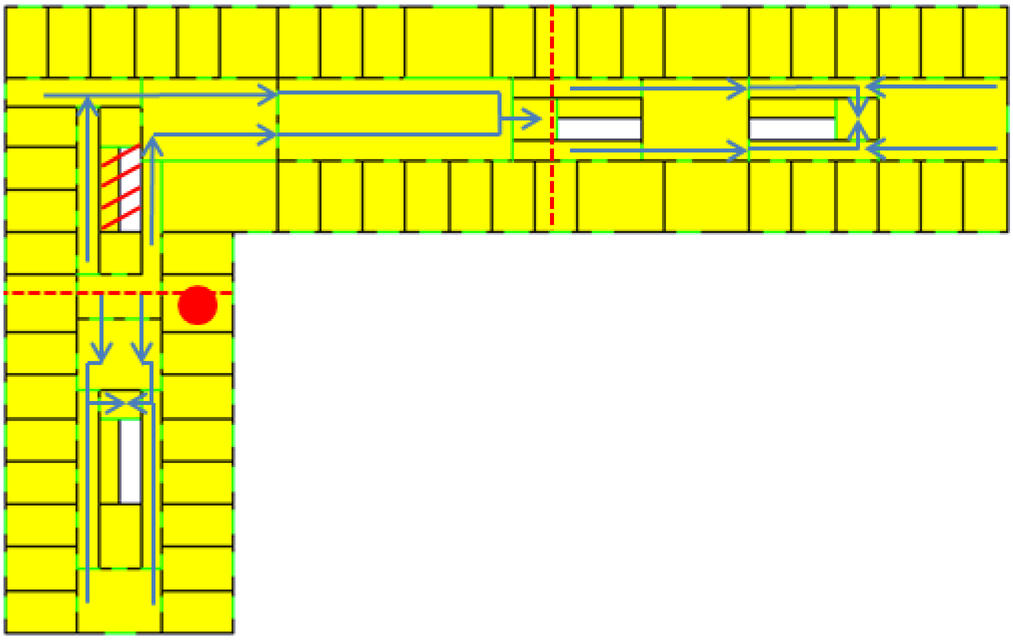

Figure 6-3 - Example use of advanced heuristics

6.4.3 Dynamic Route Planning System Improved Algorithm

Alternative suggestions for improving the system that do not involve the advanced heuristic methods discussed above would centre on making changes to the DRPS algorithm. The system architecture where a number of solutions are generated and evaluated independently of each other is a perfect candidate for parallelisation. This could be achieved using either central processing unit (CPU) or graphics processing unit (GPU) processing but the focus should be on the later due to the vast number of parallel processes that a GPU is capable of performing. For example, when using a CPU with four hyper threaded cores (as per the computer used for this project) 8 parallel processes are possible. Meanwhile, a GPU, for instance the NVIDIA G80, is capable of supporting 12288 active threads [45]. One downside of parallelising this system is that it would no longer be possible to terminate solution evaluation when they have reached the cut off level for danger cost or time but this issue would be heavily outweighed by being able to evaluate thousands of solutions simultaneously. However as the search space enlarges even further than shown here as it would be likely to do if the system was implemented in a large real world building, the chances of finding a near optimal solution in real time are still low, even with such processing capabilities. This is not to say that this is a dead end, but to prove useful further improvements to the DRPS would have to be made, particularly consideration of the effect of contraflow on occupant movement.

It would also be possible to implement a sophisticated evolutionary algorithm [28], most likely along with some form of parallel processing. The system as it stands represents a very basic form of evolutionary algorithm as when a new system execution begins, the first solution is based on the best found solution from the previous execution. To take this to the next stage in terms of EAs, it would be necessary to develop a method for determining which individual paths chosen in that solution contributed to it being chosen as "best found".

When considering both of these possible system improvements it is necessary to revisit the practicality issues involved. There are several assumptions associated with MSR steering that may violate realism to an extent where it is necessary to implement further heuristics to combat such issues. One particular requirement is to prevent occupants in one initial location from being instructed in different direction, as expecting real life occupants in a real fire event to follow such paths precisely is certainly misguided, especially if the occupants know each other.

6.5 Final Recommendations

It is necessary to provide recommendations for what is deemed to be the most promising incarnation of an intelligent egress system, from the results and discussion presented throughout this thesis. Results have demonstrated conclusively that live sensor data, to the precision assumed throughout this project, can be exploited to improve overall evacuation safety when this is quantified by total FED. The scope for which evacuation safety could be improved increased with scenario complexity and hazard severity and the dynamic aspects of the system where demonstrated to be of utmost importance in all but the most benign environments. Therefore all of the following recommendations for the implementation of a real life intelligent egress system and the important areas for future research will focus entirely on dynamic steering methods.

Multiple solution (MSR) steering did show an advantage over fastest path (UFP) steering in situations where the number of safe to use, crucial means of egress changed throughout the scenario. Naturally, this is where such a system would be expected to excel but these advantages could probably be achieved by implementing further heuristics as described in section 6.4 and with less demand on computational resources. This is why it is recommended that any further research continues with these ideas rather than attempting to increase the output potential or “power” of the DRPS by alternative methods. The justifications for this decision are also largely attributed to practicality issues that are essential to consider if such a system is to be installed in a real building.

A list of these practicality advantages includes:

- A greater range of information conveying methods are possible.
- Instructing occupants initially located in the same or similar area in different directions, is avoided, thus increasing the likelihood of the instructions being followed.
- Contraflow is avoided or minimised, therefore reducing uncertainty in solution evaluation.

It should be noted that the solution generation and evaluation is not recommended to be omitted completely and it should be used as a sanity check for heuristic generated solutions and can be used as a back-up if required. The utilisation of accumulated movement data to improve solution evaluation accuracy is most likely to have a positive impact if used to infer large differentials between detected and expected movement patterns. A possible example being if there was a large temporary object blocking a section of corridor that was not included within the DRPS. Adding a sensor linked predictive fire model is an important next step, but it is recommended that the information obtained from this is not used to generate overly detailed predictions. This should instead be utilised to make more general predictions regarding if important evacuation routes are likely to become compromised by hazardous conditions.

This project has taken previous works [6] and applied similar ideas to more complex scenarios. The methods of testing have also been improved and FED has been utilised as the measurement of comparative evacuation success for the first time. In the future it is hoped that a system similar to the one demonstrated in this project will be combined with some other projects' [13] hardware capabilities to allow real life testing of advanced "intelligent egress" concepts. This project's contribution to knowledge is to demonstrate the potential benefits to egress safety in the built environment of generating successful evacuation plans in real time, while using FED as a defining measurement, from limited sensor data, by use of simulated evacuations.

7 Conclusions

The aim of this project was to demonstrate that utilising live building sensor data to generate real time evacuation plans that are used to influence occupants' choice of egress route, can improve evacuation safety when fractional equivalent dose (FED), summed across all occupants, is used as the primary measure of success. The method by which this is demonstrated was by comparing steered and un-steered CRISP simulations across a range of building layouts and fire scenarios. A dynamic route planning system (DRPS) was developed to exploit the simulated sensor data and generate evacuation plans in real time. Various levels of system sophistication and steering methods were also explored and a further goal was to determine the circumstances, in terms of building layout and fire severity, under which the DRPS had the greatest potential impact on evacuation safety. It was also necessary for these goals to be achieved through the use of modest, readily available computational resources and that the level of information derived from sensor data is assumed to be accurate to an extent that reflects what is possible given current technology.

When considering the overall results from each scenario, the goal of demonstrating that influencing egress route choice improves evacuation safety, was clearly achieved. The hypothesis that increased scenario complexity leaves a greater potential for safety to be enhanced by the DRPS was also proven correct.

However, a direct correlation between system sophistication and margin of improved safety was not established. When considering the three scenarios it became clear that different methods of steering had greater positive impact in different circumstances. Dynamic steering resulted in lower FED levels than static steering in all but the most benign circumstances, such as those encountered in scenario 1.

A significant conclusion is that when 50% of the population was assumed to be following instructions, with the remaining occupancy being un-steered and following the human behavioural rules of the CRISP model, total FED levels were consistently lower than for totally un-steered tests. This was an important outcome as the likelihood of some occupants in a real life evacuation misunderstanding or choosing to ignore instructions is very high.

Which of multiple solution (MSR) and fastest path (UFP) steering resulted in the lowest FED levels was found to be dependent on the specifics of the building layout and the assumed initial fire location. When considering multi floor layouts; in situations where there was only one stairwell from the upper floors defined safe to use according to sensor data, UFP steering proved the most effective. This is as occurred in scenario 2, where there were only two stairwells between each floor, so when one was compromised by smoke there was no choice of alternative path. Conversely, if there were multiple safe stairwells available then MSR steering would result in decreased FED levels. This occurred in the more realistic and complex scenario 3, as there were four stairwells between each floor and usually at least 2 of these would be defined as safe to use. Another factor that impacted on the effectiveness of MSR compared to UFP steering is the extent to which the environment changed throughout the scenario, in particular if a second or third stairwell became smoke inundated part way through an event. Under such occurrences, MSR steering was again proven more effective.

The utilisation of accumulated occupant movement data with the aim of improving the accuracy of solution evaluation by making predictions as to how occupants move through certain areas of the building was also explored. The effectiveness of this method in further lowering FED levels can be concluded as negative. This result can most likely be attributed to method by which the accumulated movement data was obtained. When simulated trial evacuations were carried out, the manner by which occupants would have moved throughout the building would have resulted in very little, if any contraflow occurring. During tests where this data was used to steer occupants, contraflow was likely to occur and thus, the validity of the predictions regarding node movement speed and working area was negated. However, to conclusively write off this topic, would require further investigation and possibilities for improving how accumulated data could be utilised more effectively were discussed.

It can be concluded that MSR steering is more effective at reducing total FED levels when there are a range of significantly different routes to choose between, as this allows the evacuating occupants to be spread over multiple routes, clearing areas of the building more quickly. UFP steering is more effective when the building layout is relatively simple or there is an obvious optimal choice of route for the majority of occupants. Additionally, the greater extent to which the environment changes throughout the scenario, the more effective MSR steering becomes.

A major conclusion regarding steering type is that dynamic is more effective than static in any scenario where there is a significant threat to the safety of the occupants and is therefore the final recommended method. It can be also concluded that the ability to continually update route instructions as the scenario evolves is one of the most important attributes of an “intelligent egress system”.

This project has successfully demonstrated the potential of intelligent egress through the use of simulated evacuations. A novel dynamic route planning system has been developed and tested across a range of different scenarios using FED as the measurement of success. Evacuation plans have been shown to be producible in real time, necessary for practicality purposes if used in a real environment. This has been achieved using modest computational resources. The results presented here will hopefully encourage further works, including full scale trials. Specific recommendations have been made regarding the most promising areas for further study. This includes focusing on a more building specific, heuristic approach, an example of which was discussed

8 Bibliography

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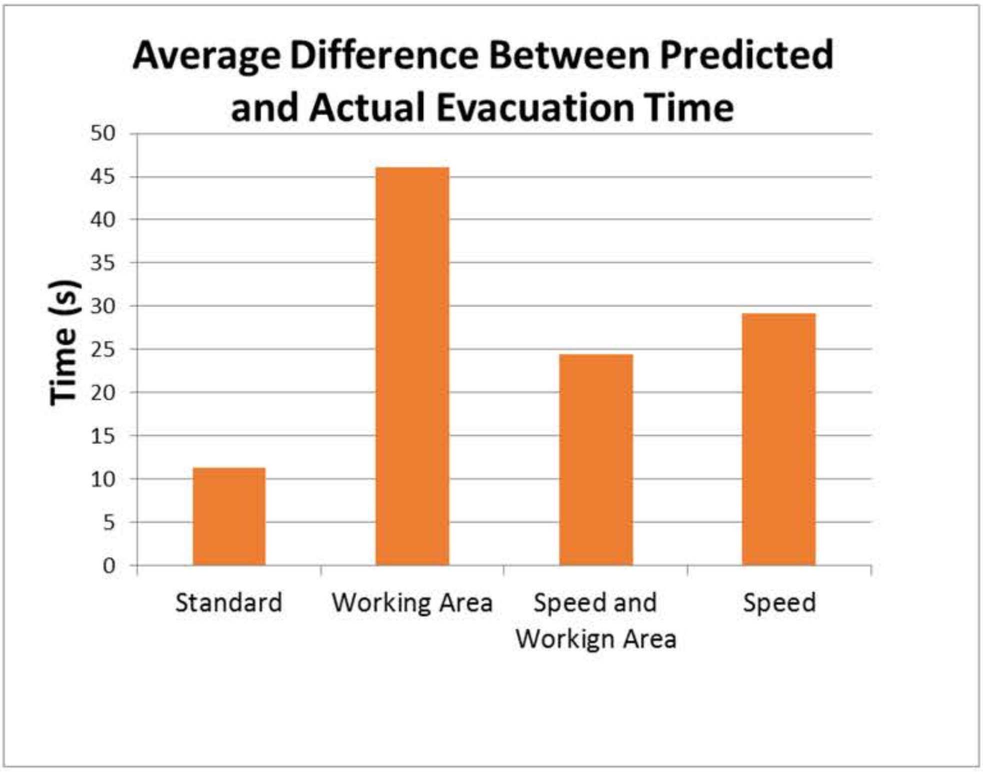
9 Appendices

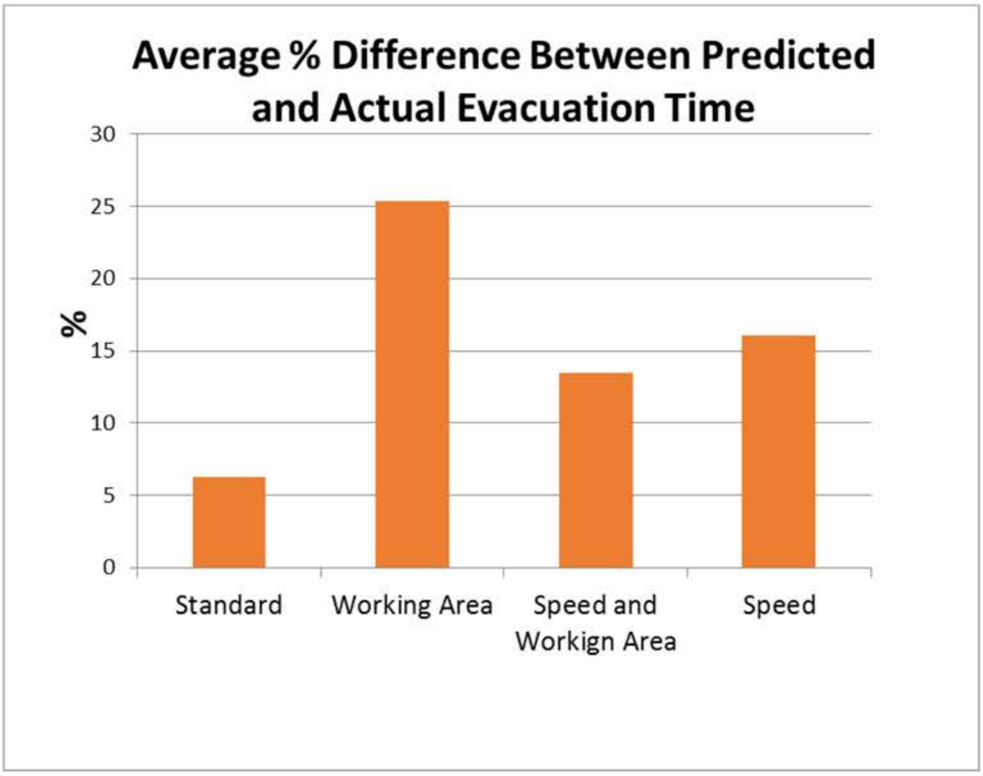
Appendix 1 - Analysis of Accumulated Movement Data

Using the building layout in scenario 2 (chapter 4), many mock trial evacuations were carried out and monitored by the DRPS. From these results the adjusted working area and free movement speed for each node was calculated. These adjustments were then tested to determine how accurate possible predictions derived from this data would be. CRISP was then used to initiate a new scenario with a different initial population location set than which was used to obtain the data. The DRPS would evaluate a base line solution (no hazard involved) using each of the following rules:

- Un-adjusted working area or node speed.
- Working area adjusted only.
- Working area and node speed both adjusted.
- Node speed only adjusted.

This gave a predicted evacuation time for each of the above. These times were compared to the CRISP simulation evacuation time. This was repeated over a range of initial population sizes and location distributions. The results, showing how accurate the DRPS is at predicting total evacuation time, while following various adjustments is shown in the following graphs.


Average Difference Between Predicted and Actual Evacuation Time
Time (s)
0
5
10
15
20
25
30
35
40
45
50
Standard
Working Area
Speed and Workign Area
Speed


Average % Difference Between Predicted and Actual Evacuation Time
%
0
5
10
15
20
25
30
Standard
Working Area
Speed and Workign Area
Speed

It is obvious to see that the data accumulation based predictions are all considerably less accurate in this situation than the standard DRPS predictions. The standard DRPS settings are shown here to be accurate (6% discrepancy). The most accurate (or least inaccurate) data accumulation based prediction was when both node working area and speed were adjusted (13% discrepancy).

Appendix 2 - 50 George Square Building Layout.

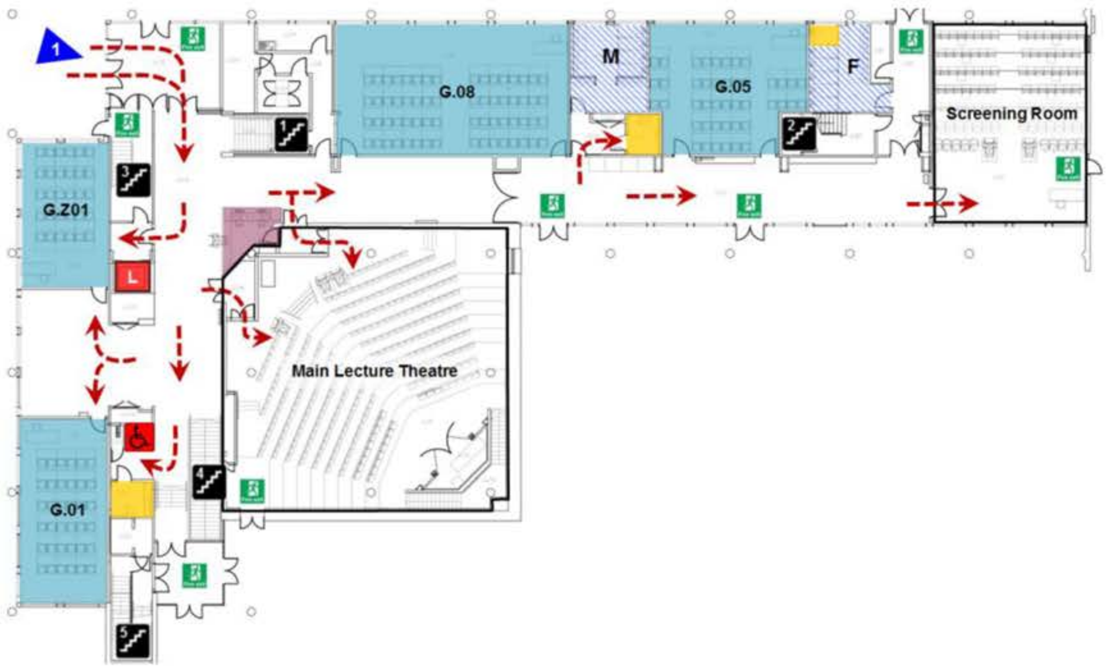


Figure 9-1 - Ground Floor [43]

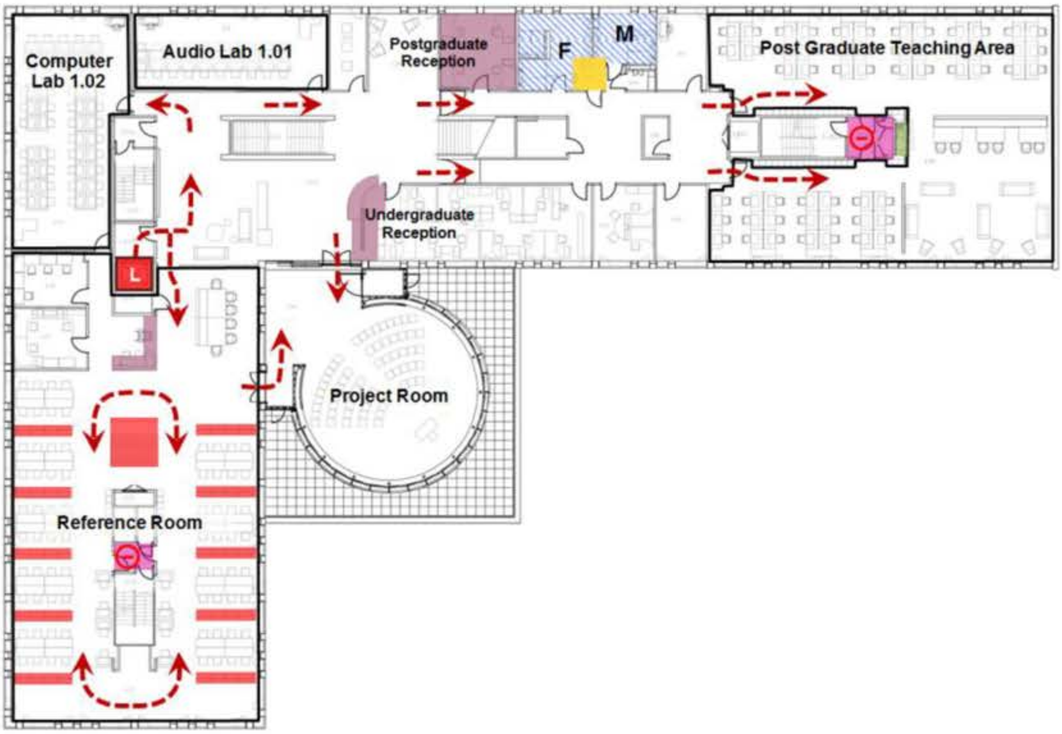


Figure 9-2 - 1st Floor [43]

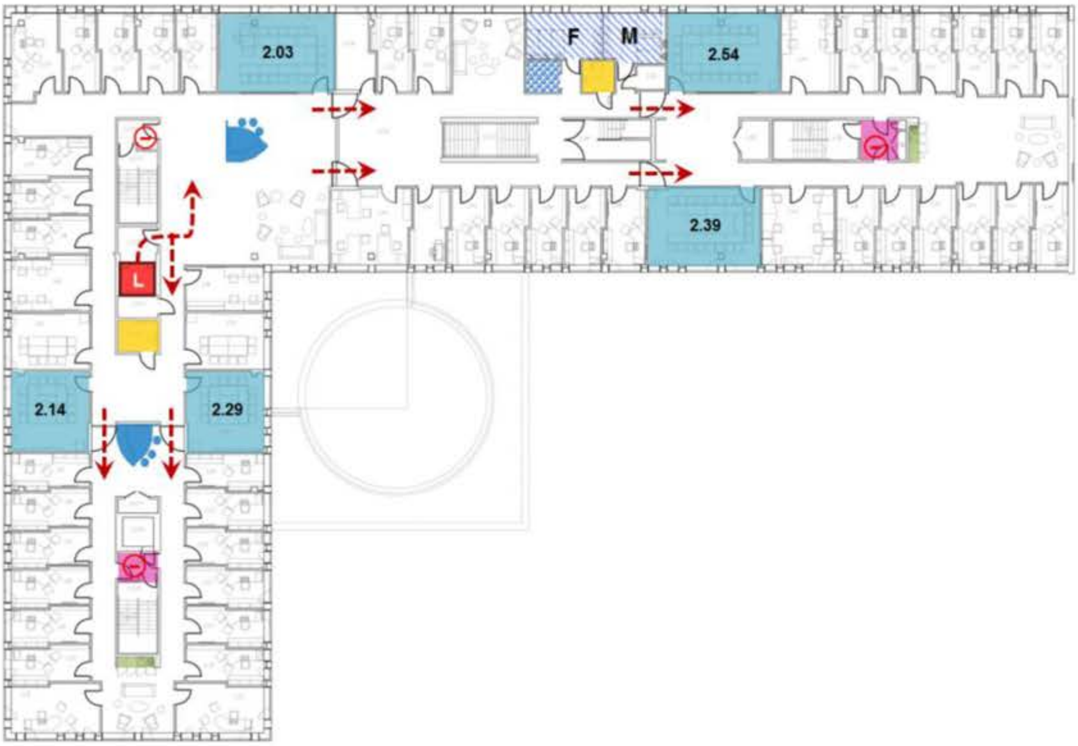


Figure 9-3 - 2nd Floor [43]

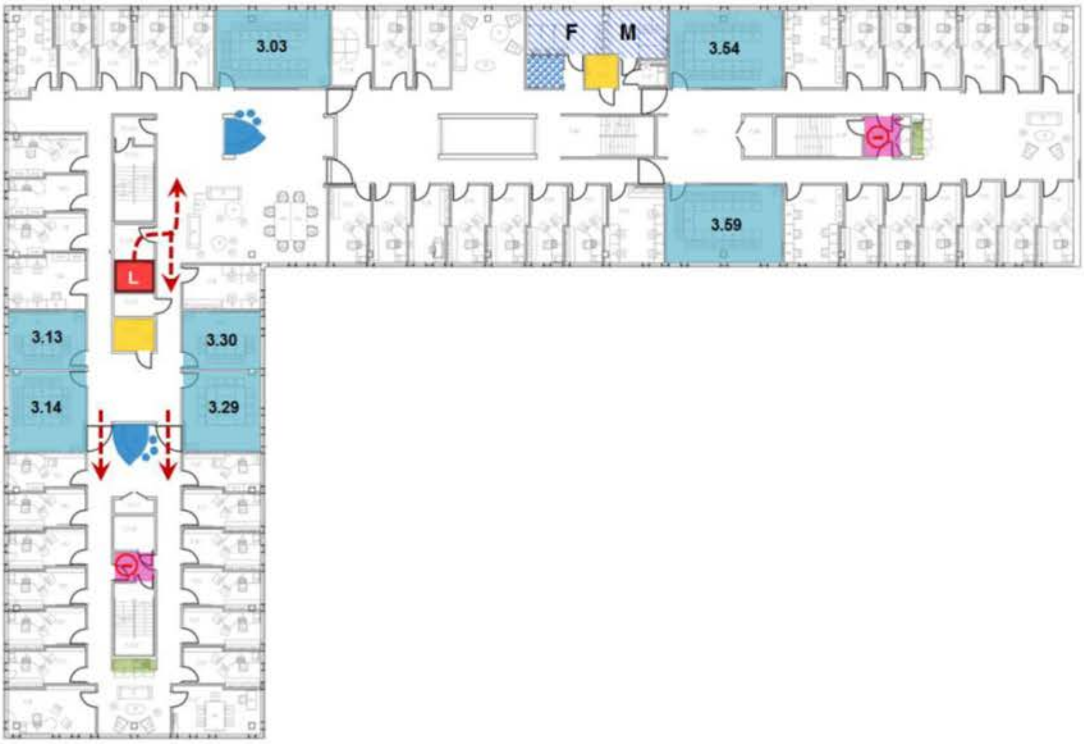


Figure 9-4 - 3rd Floor [43]

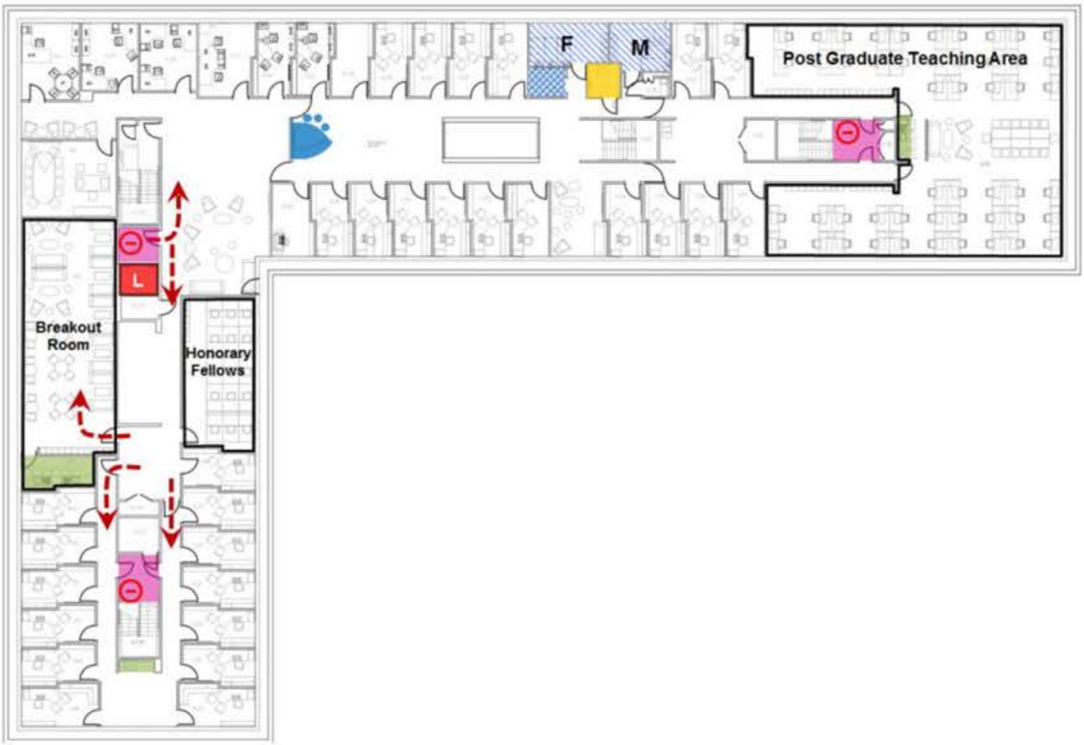


Figure 9-5 - 4th Floor [43]